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EFFECTS OF LEAN MANUFACTURING ON SUSTAINABLE PERFORMANCE: AN EMPIRICAL STUDY ON COLOMBIAN METALWORKING INDUSTRY

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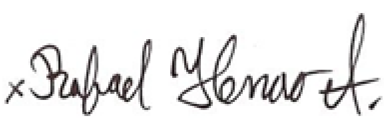

Rafael Henao Arango

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This thesis is dedicated to the memory of my late grandfather Eduardo Arango. Without his legacy this work would be of no practical relevance to our region.

ABSTRACT

Effects of lean manufacturing on sustainable performance: an empirical study on Colombian metalworking industry

Sustainability has become an outmost priority for manufacturing companies due to increasing pressure from multiple stakeholders. Employees, customers, and society in general, call for a reduction in the adverse effects on the environment and an improvement in social outcomes derived from industrial operations. At the same time, shareholders push for better economic and financial results in an overly competitive and globalized market, which requires continuous improvements to maintain a competitive edge. In this context, lean manufacturing has established itself as dominant paradigm in manufacturing operations, which allows companies to pursue improvements in several key competitive priorities such as, quality, flexibility, delivery time, and cost. However, concerns have been growing in the scientific community regarding how lean manufacturing implementation can effectively allow companies to achieve their sustainable development goals, or, in the contrary, if the resources required for a successful lean implementation can result in a detriment of environmental and social performance.

This doctoral thesis intends to help close the knowledge gap regarding the effects of lean manufacturing on sustainable performance from a triple bottom line perspective. Based on a careful review of the state-of-the-art literature, two models to describe the interaction between lean and sustainability were proposed. The first is called the “sand-cone” model, which poses that performance improvements derived from lean implementation are cumulative on each one of the sustainable performance dimensions. The proposed sequence starts with lean improving operational performance, which settle the bases and provide resources to drive performance improvements in the environmental dimension, which in turn, can materialize into social performance improvements. The second model is called the “trade-offs” approach. In this case, the resources required to improve one dimension of sustainability clash with the resources required to maintain another (or the other two), therefore, creating a detriment in performance.

To test the proposed hypotheses, data was gathered from a sample of Colombian metalworking companies and processed using structural equations models. The results presented evidence of lean manufacturing having positive effects on sustainable performance and also support the cumulative “sand-cone” model. In the case of the “trade-offs” model, conclusive evidence was not encountered. However, partial evidence suggests that when lean manufacturing is employed to simultaneously pursue improvements in all sustainability dimensions, possible trade-offs can occur in detriment of social performance. The results represent a novel theoretical and scientific contribution as they propose and test the two aforementioned models in the context of sustainability, providing further knowledge into its interaction with lean manufacturing. They also contribute to practitioners by providing a tested path for companies to improve their performance in a cumulative sequence that will provide better long-term results. Finally, Colombian companies and government organizations can profit from the results to promote successful lean manufacturing implementations that improve competitiveness, while improving also the sustainability of the metalworking productive chain.

Keywords: lean manufacturing, sustainability, performance, metalworking

RESUMEN

Efectos de lean manufacturing en el desempeño sostenible: un estudio empírico en la industria metalmecánica colombiana.

La sostenibilidad se ha convertido en una prioridad para las compañías manufactureras a raíz de las crecientes presiones por parte de diferentes grupos de interés. Empleados, clientes, y la sociedad en general, claman la reducción de los efectos adversos en el medio ambiente y el mejoramiento de los resultados sociales derivados de la operación de las industrias. Al mismo tiempo, los accionistas presionan por resultados económicos en un mercado altamente competitivo, que requiere mejoras continuas para mantener la ventaja competitiva. En este contexto, lean manufacturing se ha establecido como un paradigma dominante en operaciones manufactureras, permitiendo a las compañías perseguir mejoras en múltiples prioridades competitivas tales como, calidad, flexibilidad, tiempo de entrega, y costo. Sin embargo, han aumentado las preocupaciones en la comunidad científica frente a como la implementación de lean manufacturing puede efectivamente permitir alcanzar los objetivos de desarrollo sostenible de las empresas, o, si por el contrario, puede resultar en el detrimento del desempeño social y ambiental.

Esta tesis doctoral pretende contribuir a cerrar el vacío del conocimiento acerca de los efectos de lean manufacturing en el desempeño sostenible desde la óptica de la triple línea base. A partir de una cuidadosa revisión del estado del arte en la literatura, dos modelos para describir la interacción entre lean y sostenibilidad fueron planteados. El primero, llamado “cono de arena”, propone que las mejoras en desempeño derivadas de la implementación de lean manufacturing son acumulativas en cada dimensión de desempeño sostenible. La secuencia propuesta comienza con lean mejorando el desempeño operativo, lo cual sienta las bases y provee los recursos para estimular mejoras en el desempeño de la dimensión ambiental, las cuales, pueden materializarse en mejoras del desempeño social. El segundo modelo, es llamado el enfoque de “compromisos”. En este caso, los recursos requeridos para mejorar una dimensión de sostenibilidad, riñen con los recursos requeridos para mantener otra (o las otras dos), creando entonces un detrimento en el desempeño.

Para probar las hipótesis propuestas, se recolectaron datos de una muestra de empresas metalmecánicas colombianas, los cuales fueron procesados usando modelos de ecuaciones estructurales. Los resultados evidencian que lean manufacturing tiene efectos positivos en el desempeño sostenible y adicionalmente soportan el modelo “cono de arena”. Para el caso del modelo de “compromisos” no se encontró evidencia concluyente. No obstante, la evidencia parcial sugiere que al emplear lean manufacturing para perseguir simultáneamente mejoras en las dimensiones de sostenibilidad, existe la posibilidad de obtener compromisos que llevan al detrimento del desempeño social. Los resultados representan una contribución al ámbito teórico y científico al proponer y probar los dos modelos mencionados en el contexto de la sostenibilidad, entregando conocimiento adicional respecto a su interacción con lean manufacturing. También contribuyen a la práctica al proveer un camino probado para que las compañías puedan mejorar su desempeño en una secuencia acumulativa. Por último, las compañías colombianas y entidades gubernamentales pueden sacar provecho a los resultados para promover la implementación exitosa de lean manufacturing e incrementar la competitividad, al mismo tiempo que se mejora la sostenibilidad.

Palabras clave: lean manufacturing, sostenibilidad, desempeño, metalmecánica

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ABBREVIATIONS

- α: Cronbach's alpha
- ANDI: Asociación nacional de industriales *(National industrial association)*
- APQP: Advanced product quality planning
- AR: Action-research
- AVE: Average variance extracted
- BS: Bollen-Stine
- CFA: Confirmatory factor analysis
- CFI: Comparative fit index
- CMB: Common method bias
- COP: Colombian Peso
- CR: Composite reliability
- CSF: Critical success factors
- CSR: Corporate social responsibility
- CVI: Content validity index
- DANE: Departamento administrativo nacional de estadística *(National administrative statistics department)*
- df: Degrees of freedom
- EAN: Encuesta anual manufacturera (*Annual Manufacturing survey*)
- EFA: Exploratory factor analysis
- EP: Environmental performance
- FMF: Fit manufacturing framework
- GDP: Gross domestic product
- GLS: Generalized least squares
- GM: Green manufacturing
- GRI: Global reporting initiative
- GSCM: Green supply chain management
- HPM: High performance manufacturing
- HRM: Human resources management
- ISIC: International standard industrial classification
- ISO: International standards organization
- JIT: Just in time
- KMO: Kaiser-Meyer-Olkin
- KPI: Key performance indicator
- LM: Lean manufacturing
- ML: Maximum likelihood
- OEE: Overall equipment effectiveness
- OM: Operations management
- OP: Operational performance
- PCA: Principal component analysis
- RMSEA: Root mean square of error approximation
- R&D: Research and development
- SCM: Supply chain management
- SDG's: Sustainable development goals

- SEM: Structural equation modelling
- SLR: Systematic literature review
- SME: Small and medium enterprise
- SMED: Single minute exchange of dies
- SP: Social performance
- SPC: Statistical process control
- SSTP: Sustainable performance
- TBL: Triple bottom line
- TPM: Total productive maintenance
- TPS: Toyota production system
- TQM: Total quality management
- USD: United States Dollar
- VSM: Value stream mapping
- WIP: Work in process

UNITS AND CONVENTIONS

The present document is written in American English language. Names of persons and institutions will be preserved in their original language, as well as non-English acronyms and abbreviations. Where needed, literal translation of institution names and acronyms will be presented in parenthesis next to the original language name.

The International System of units will be used since it is the ruling measure system in Colombia. In necessary cases, alternate units will be presented in parenthesis next to the conventional units.

Decimal numbers are marked by commas (,), whilst a point (.) will be used as thousand separators where needed. The number of decimal places will be variable according to the magnitude of the measure that is being represented, and the relevancy of it decimal numbers.

Monetary dimensions originating from Colombia will be presented in Colombian Peso (COP), with their approximate equivalent on United States Dollars (USD) according to the average exchange rate for the year of measurement. All other monetary dimensions will be presented in USD.

On text citations and references will be applied according to the Harvard citation standard (name, year), and “et al.” abbreviation will be used for more than two authors. In the case of two citations having the exact same authors and year of publication, each citation will be differenced with a low case letter immediately after the year.

INTRODUCTION

Sustainability has become a major concern for manufacturing companies worldwide in recent years (Martínez León and Calvo-Amodio, 2017). Although sustainable development is not a new concept, only in the last couple of decades the increasing pressures from different stakeholders (including customers, governments and communities) has raised enough awareness to be included into the organizational priorities of most companies. Despite many industries nowadays being aware of the need to implement sustainable manufacturing practices, it is still difficult and unclear for them how to translate those requirements into their day-to-day decisions (Burritt and Schaltegger, 2014; Dočekalová and Kocmanová, 2016).

Within academic and scientific fields sustainability research has gained great relevance from some years. However, in the industrial and manufacturing settings the concept and its importance has not yet been fully accepted, with many companies still focusing in the economic bottom-line and disregarding the urgency for a more comprehensive approach. In spite of this, several drivers such as increased regulations, more informed and demanding customers, non-renewable resources scarcity, among others, increase the pressure on companies to address sustainability issues or risk being progressively relegated. Therefore, there is growing urgency for companies to profit from the sustainability path already covered by the scientific community, and from their everyday developments. Nevertheless, a proper, long-term, sustainable manufacturing paradigm, that is capable of rendering the shareholders expected economic benefits, while contributing with improvements in the social condition of the employees and surrounding communities, and being free of irreversible harm to the environment, is still looked as an utopic ideal in most cases, instead of being a clear path to follow (Ciannella and Morioka, 2018).

To help close the gap between “idealistic” sustainability definitions and goals that are difficult for companies to monitor and implement in their decision-making processes, Elkington (1994) proposed the triple bottom-line (TBL) concept. The TBL approach to sustainability calls for companies to focus in developing simultaneous efforts to improve the “3Ps”: people, profits, and planet. In other words, it is expected that companies can be able to produce the expected economic results, while improving their environmental and social outcomes. Nonetheless, many companies have been giving priority to their economic outcomes, disregarding (or deteriorating) their environmental and social performance. This situation can result more alarming in developing countries (Distelhorst et al., 2017).

Manufacturing industries strive daily to success in an overly competitive globalized market, where sustainability expectations from different stakeholders add to customers that are more informed every day, have more buying options, and have high expectations regarding quality, delivery time, innovation, customization, and of course, demand competitive costs. In this environment, lean manufacturing has gained significant relevance to meet those multiple (and often contradictory) expectations (Resta et al., 2017). For many scholars, the principles and main practices comprising lean manufacturing originated in Japan after the second world war and came somehow naturally within the Japanese culture (Danese et al., 2018; Gupta, 2016). Yet, by the late second half of the twentieth century, western companies were still struggling to adapt their mass production systems to a more flexible (i.e. lean) environment in that met customer expectations (Womack et al., 1990).

However, with the arrival of the twenty first century, lean manufacturing began to stablish itself as one of the leading manufacturing paradigms worldwide, thanks to its proven benefits on many operational level indicators such as cost, quality, flexibility, and inventory reductions, among others (Negrão et al., 2017). Although said operational improvements are highly supported in scientific literature, as well as commonly perceived by practitioners and companies, what it is not yet completely clear is how lean manufacturing impacts and interacts with the other two pillars of TBL performance, the environmental and social ones (Chavez et al., 2020).

With the boom of lean manufacturing in recent years, along with the growing concerns regarding long-term sustainability of manufacturing operations and their impacts on the TBL, the two fields of study have converged into a series of inevitable questions, among them: which are the effects of lean manufacturing on each pillar of triple bottom-line performance? and, how the different dimensions of TBL performance interact in the presence of lean manufacturing. Research aimed at providing answer to those questions have gained high interest in the last five years, although no consensus has been achieved, and results available in literature remain contradictory in many cases (Sajan et al., 2017; Varela et al., 2019).

Through the review of existing state of the art literature, a knowledge gap was identified regarding the effects of lean manufacturing on sustainability. Therefore, this thesis aims to help close said knowledge gap by providing answer to the following research question: what is the effect of Lean Manufacturing strategies on Colombian metalworking industry sustainable performance from a triple bottom line approach?. To provide a better understanding of the studied phenomenon, three research sub-questions are also approached. First, which dimensions can be used to properly describe and measure the degree of lean manufacturing implementation on a manufacturing industry?; second, which dimensions can be used to properly measure the operational, environmental and social performance within a company?; and finally, how is the nature of the interactions between operational, environmental and social performance in presence of lean manufacturing strategies among the Colombian metalworking industry?, are they cumulative, exclusive, or independent?

In line with the proposed research questions, the main objective will be to "*Identify and analyze the effects of Lean Manufacturing implementation on sustainable performance, in the context of Colombian metalworking industry*". To achieve said purpose, five specific objectives were proposed that will be covered through the different chapters of this document. First, identify the current state of the art and state of the practice in the research field to develop a conceptual framework that will result applicable to the study. Second, propose different conceptual models (from the state-of-the-art) that explain the relationships between lean manufacturing and sustainable performance. Third, design a set of dimensions suitable for measuring the degree of implementation of Lean Manufacturing, and the performance of each one of the three TBL pillars (i.e. operational, environmental, social). Fourth, design and apply a data collection instrument and statistically process the collected data through multivariate methods to test the research hypothesis. And fifth, critically analyze the results to answer the research questions and propose new research lines.

From the state-of-the-art literature on both topics, two hypothetical models were proposed to explain the effects and interactions of the studied variables: lean manufacturing and sustainable performance. The first proposed model is called the "sand-cone" approach, which states that lean manufacturing can produce cumulative improvements on sustainable performance, starting with operational performance, which in turn, helps with the improvement of environmental performance, and finally, benefits social performance. The second model is called the “trade-offs” model. In this model, it is hypothesized that improvements in one dimension of the TBL, will come at the expense of other (or the other two), as a result of the required resources to drive performance in one single direction. Although both approaches have been previously employed and tested in operations management, this research presents a novel contribution in adapting (and testing) them to explain the relationships between lean manufacturing and sustainability.

A survey-based empirical approach was employed to gather relevant data in a sample of Colombian metalworking companies allowing to answer the aforementioned questions. From a methodological perspective, a mixed approach was used, with a qualitative stage to construct the state-of-the-art, declare the knowledge gap, and draw the operationalization of the studied variables (lean manufacturing implementation level, and sustainable performance), followed by a case study aimed at closing the gap between the theoretical concepts and terminology of said variables and their application in the practical environment of the studied object (i.e. the Colombian metalworking industry). Then, with the data from the qualitative stage, a quantitative stage followed to test the proposed hypotheses with the data gathered through the purposely design survey, and the subsequent analysis of the obtained results. From an ontological perspective, the research is approached from a *critical-realism* position, and, from an epistemological perspective, it adheres to a *post-positivist* viewpoint. This allows to draw objective conclusions from the gathered and analyzed data through the scientific method and it is expected that those conclusions can have a certain degree of generalization on the studied object. However, it also acknowledges that the researcher backgrounds and previous experience have an influence on its observations and conclusions.

The results presented evidence of lean manufacturing having positive effects on each TBL performance pillar, when evaluating them separately. However, when all TBL pillars are accounted simultaneously in the presence of lean manufacturing, the obtained results support the cumulative “sand-cone” model, with the direct effects of lean on environmental and social performance becoming not significant, but with the proposed sequence of lean→operational→environmental→social performance showing strong evidence. Regarding the case of the “trade-offs” model, conclusive evidence was not encountered. However, partial evidence suggests that when lean manufacturing is employed to simultaneously pursue improvements in all TBL pillars, possible trade-offs can occur in detriment of social performance.

There is no universal recipe for LM implementation (Negrão et al., 2017) and cultural context is highly influential on the success of lean (Danese et al., 2018; Psomas, 2021). Therefore, the studied object is limited to Colombian metalworking companies in order to provide answers to the research questions in said context. This allows to concentrate in the studied phenomenon without the need to cope with intra-context factors that might arise in a multi-sector and multi-country research. Also, while research on the relationships between LM and TBL performance is still on an exploratory phase, the proposed models could be easily replicated in the future in other contexts, while the obtained results will definitively help to close the theoretical gaps on the subject, while contributing from a practical point of view to Colombian companies which have scarce information available on LM implementation guidelines purposely designed for the country socio-cultural context (Hernandez et al., 2020), and often have to rely on studies conducted in other Latin or developing countries facing similar challenges (Chavez et al., 2020; Walter and Paladini, 2019), to adapt said guidelines to their reality.

From a theoretical perspective this thesis provides a valuable contribution showing evidence of positive effects of lean manufacturing on sustainable performance (under the TBL approach). This helps to close the knowledge gaps identified in this area and provides empirical grounds to develop and perfection integrating theories between both paradigms. Another worth noticing contribution relies on the extension of two conceptual approaches (the sand-cone and trade-offs) that were previously untested in the field of sustainability, which in turn provides guidelines of how the different dimensions of sustainability interact in manufacturing operations. In addition, the results present a practical contribution for managers and companies to design better and more efficient approaches to lean manufacturing implementation, while addressing the much-needed improvements on sustainable performance without compromising their stakeholders economic and operational expectations. Finally, regarding the studied object (i.e. the Colombian metalworking industry), the so-called “triple-helix” (government, universities, and industries) can take profit from the results to develop public policies, academic programs, and research and development projects, that materialize in competitiveness gains for the Colombian companies, and their alignment with worldwide sustainability expectations.

To support the aforementioned claims and following methodological rigor of the empirical research paradigm, the present document is structured as follows: Chapter 1 covers the theoretical framework, where base-line concepts, models, theories, frameworks, and previous research results extracted systematically from state-of-the-art literature are reviewed and critically analyzed, in order to identify the knowledge gap. Chapter 2 describes the employed methodology, starting with the declaration and justification of the selected research paradigms, followed by the definition of the research hypotheses, and the operationalization of the independent (lean manufacturing) and dependent (sustainable performance) variables. Chapter 3 presents the obtained results, covering from the empirical validation of the designed survey instrument, the collection of data from the defined sample, and finally, the statistical processing of the data through structural equation models. Finally, Chapter 4 introduces the discussion of the obtained results in light of the theoretical backgrounds covered in the first chapter, to then draw the final conclusions of the research, along with theoretical and practical implications, limitations, and further paths for research.

CHAPTER 1. THEORETICAL FRAMEWORK

1.1. Introduction

This doctoral thesis revolves around two major topics: sustainability and lean manufacturing. Both topics are relatively new in the context of Colombian metalworking industries. Lean manufacturing can be traced back to the sixties' in Japan (Kleindorfer et al., 2005), and as late as the eighties and nineties in western countries (Hayes and Wheelwright, 1984; Womack et al., 1990), as an alternative to traditional "mass production" strategies, favoring competitive priorities such as flexibility, quality and delivery, without excessively compromising the cost of the product (Hallgren and Olhager, 2009). This can be achieved via waste minimization and system efficiency maximization approach (Nujoom et al., 2017; Ruben et al., 2018).

On the other hand, the sustainability concept has evolved from the late twentieth century form concerns arising regarding the environmental, and later societal, irreversible impacts of human activities. First mentions to sustainability (related to the actual concept) in academic literature can be found in Goodland (1980) and Dyer (1982), both concerning about environmental protection and responsible use of resources. However, it was until the "Brundlandt report" (World Commission on Environment and Development, 1987) that sustainability (and specifically the need for sustainable development) was posted as a world priority. By the mid nineties', Elkington (1994) proposed the "triple bottom line" approach to sustainable development, as a balance between environmental, social and economic performance dimensions (Abdul-Rashid et al., 2017).

Despite the relatively young age of lean manufacturing and sustainability (compared with more developed research topics in OM and business fields), both have evolved into complete fields of study with a vast theoretical background developed in the 21st century (especially in the last decade). Different paradigms, approaches and frameworks have been proposed (and in some cases tested) in each field, and more recently (in the last five years), theoretical bridges have begun to develop between lean manufacturing and sustainability concepts.

This makes the relationship of lean manufacturing and sustainability a topic of rapidly growing interest in academic literature, which nevertheless, still have many gaps to be filled and questions to be answered (Martínez León and Calvo-Amodio, 2017; Nujoom et al., 2017; Sajan et al., 2017; Thomas et al., 2016; Vinodh, Ben Ruben, et al., 2016). Therefore, the purpose of this chapter is to present and discuss the relevant theoretical grounds, in both lean manufacturing and sustainability, in which this research is based, in order to provide the bases to identify and declare the knowledge gap to be approached in this research. In this context, the chapter is structured as follows: first, the theoretical framework development strategy is presented. Second, sustainability and lean manufacturing theoretical backgrounds are approached separately, and then, links and relationships between both concepts are presented and discussed in the light of the most recent research. Finally, the knowledge gap addressed in the present research is derived and declared considering the state of the art on the reviewed theory.

1.2. Theoretical Framework Development Strategy

As one of the first steps for the research development, the conceptual framework was constructed around the research topics with the aim of approaching the state of the art and state of the practice in each one of the covered fields of study. This allows to properly identify the ruling paradigms and commonly accepted theories, as well as the most recent frameworks that support the theoretical backgrounds of the proposed research. Finally, contrasts and questions resulting from those ruling paradigms allow to identify and declare the knowledge gap for this research. Figure 1 shows a summary of the covered topics.

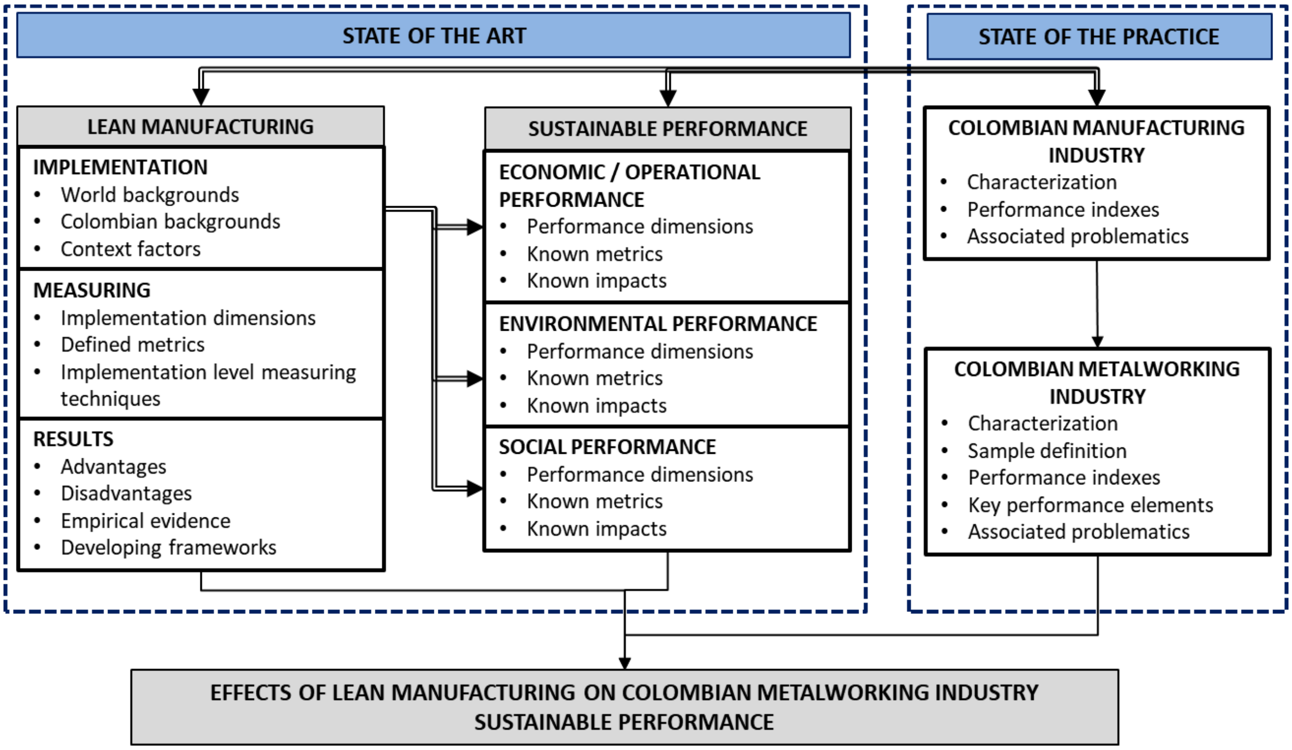

Figure 1. Theoretical framework development strategy

Literature gathered for the theoretical framework development, came from different sources, including academic and scientific journals articles, doctoral and master thesis, and reports from reliable and recognized government and non-profit organizations. The state of the art was constructed mainly following a three-phase methodology, adapted from Gahm et al. (2016) and Stindt (2017), which is shown in Figure 2. First, an unstructured narrative literature search was conducted in the topics regarding lean manufacturing and sustainability. It allows for the conceptualization of the topics and to identify the common use terminology (Ceulemans et al., 2015) and keywords to be employed in the second phase.

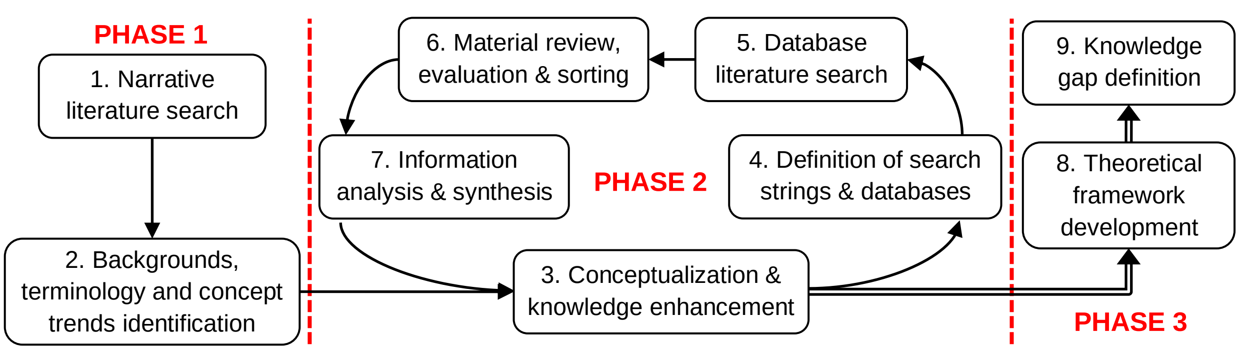

Figure 2. State of the art development methodology.

The second phase consists of a systematic literature review, through the steps described in Figure 2. The systematic literature review aims to provide objectivity, reproducibility, and transparency (Garza-Reyes, 2015), and should provide a fair approach to the state of the art literature in a given field of study. Material collection was done by applying the search strings presented in Table 1, on Scopus (www.scopus.com) from Elsevier B.V., and ISI Web of Science (www.wokinfo.com) from Thomson-Reuters. These electronic databases have the largest indexes of industrial engineering, manufacturing, operations management, sustainability and sustainable development, amongst other related topics.

Table 1. Systematic literature review search strings

String	LM keywords		Sustainability keywords
String 1	"lean manufacturing" OR JIT OR TPS	AND	Sustainability OR "triple bottom line" OR TBL
String 2	"lean manufacturing" OR "manufacturing practices" OR TPS OR JIT	AND	"operational performance" OR "operational efficiency" OR sustainability OR "sustainable performance" OR "green performance" OR "environmental performance" OR TBL OR "triple bottom line" OR "social performance"

The first search string included only the specific terms directly related to the present investigation's two main research topics, including other terms usually employed by authors to refer to LM, or forms of LM, such as JIT, or TPS. As few papers were found, the results from the first string proved that this is a relatively new research trend. In consequence, to broaden the reach of topics, the second search string was applied. The process was performed iteratively on a semi-annual basis to update the most recent literature to date, with Figure 3 a clear indication that this is a rapidly developing research topic.

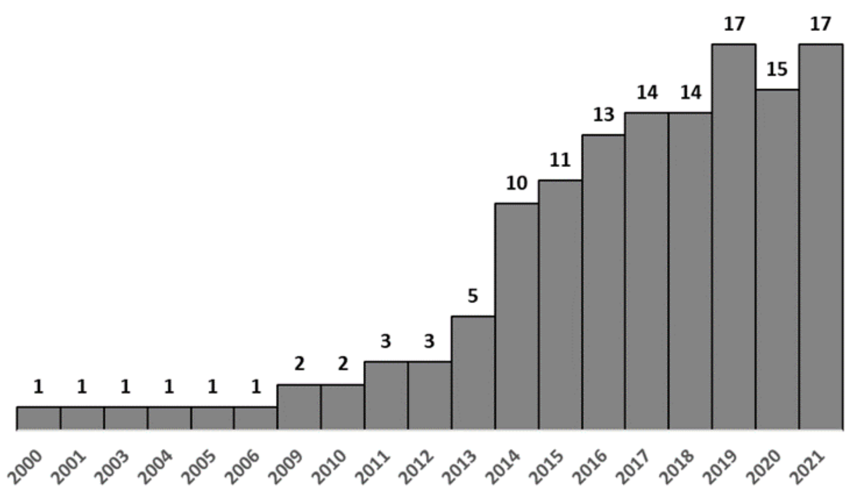

Figure 3. Evolution of lean manufacturing and sustainability related papers

The third phase comes as a result of the analysis and synthesis of papers selected from the SLR, but was also enhanced from other three sources: material (articles, thesis and reports) gathered through the narrative search, cross referencing of common citations to seminal works, and the use of My Tree of Science (ToS) (tos.manizales.unal.edu.co). This tool uses algorithms based on networks theory to create citation chains from the results of a given search string (Robledo et al., 2014). Results are organized in a tree scheme, where the roots represent the seminal studies from which the research field emerged; branches are different research trends and, finally, the leaves represent the most recent contributions to each branch.

The identification, discussion and contrasting of literature in the third phase of the adapted methodology (Figure 2), facilitates the development of theoretical grounds, pointing out to areas where further research is needed (Ceulemans et al., 2015), and ultimately leads to the declaration of the knowledge gap to be addressed in this research (Section 1.9). It also supports several decisions regarding the methodological approach presented in Chapter 2. It is important to notice that the three-step methodology adopted and the SLR review, aims to provide objectivity of the theoretical framework development (Ceulemans et al., 2015). However, there is a certain degree of subjectivity related to the own author sorting and interpretation of the identified papers, and there are intrinsic limitations of the SLR mainly related to the publications indexed on the consulted databases, which provides at least a small probability that relevant articles have been excluded (or not identified) from the theoretical framework.

Regarding the state of the practice, research of lean manufacturing and sustainability outcomes in Colombian metalworking industry remains scarce (even in Colombian manufacturing industry in general). Therefore, most relevant information comes from government documents (CONPES, national development plans, and strategic plan for technological, industrial and quality development). In addition, some institutions and guilds such as ANDI (National Industrial Association) have done previous studies gathering valuable data. Finally, doctoral and master thesis from local universities also provide useful backgrounds.

1.3. Lean Manufacturing

1.3.1. Backgrounds

From the beginning of the industrial revolution, the accelerated growth of world population, the availability in great quantities of primary resources, along with developments in extraction and processing techniques, and finally, the progressive rhythm of technological development promoted the growth of global economics in a high demand environment, providing great opportunities. Even the consecutive world wars in the first half of the 20th century did not manage to stop this phenomenon. Furthermore, even with highs and lows in world economy until the eighties, there was a world with enough resources to supply endless growth.

The end of the cold war pushed the position of capitalism to the forefront as the dominant economic model. In industry in general, the need for financially backed growth and the growing rate of markets globalization by the nineties resulted in a generalized search for efficiency and process improvement, which intended to lead to a cost cutting and consequently, a rise in profits. It is possible to observe from the research in manufacturing during that period (Ward et al., 1998), how industries and companies were primarily focused on improving the operational performance in the search for better economic results.

In this context, the application of new strategies, methods and tools to manage the value chain, gained relevance as one of the best ways to achieve the desired performance improvements and cost savings. Some of those strategies were developed years ago empirically in Japan, as a way to cope with the need for an industrial reconstruction of the country after the Second World War. That "toolbox" of manufacturing practices, primarily focused on continuous improvement, was intrinsic to the eastern culture, which in turn eased its application on Japanese companies. The strategies and tools continued to be developed and perfectioned during the second half of the XX century, and documented by industrialists, engineers and academics such as Tahichi Ohno, (1988), Eiji Toyoda and Shigeo Shingo (1989).

It is widely accepted that the importance of such management and manufacturing tools was initially seen in Japan due to the resource shortage and financial difficulties of the immediate post war era as they forced the industrialists and businesspeople to search for alternatives that would allow them to compete with the great investments in technology and capacity achieved by their North American counterparts (Liker, 2004). In this way the TPS (Toyota Production System) was born, which was a series of philosophies and strategies that focused on bringing Toyota into a world competitive environment (Pegels, 1984), making the most of the relatively little possibilities of the Japanese industrial context of the time, without the need to spend the large sums of money invested on machines and technologies like the largest manufacturers of that time, such as Ford or General Motors (Liker, 2004; Womack et al., 1990).

In spite of the emergence of Toyota into the global market, along with other widely recognized Japanese brands as Sony, Toshiba, Mitsubishi and Nikkon, among many others, during the second half of the 20th century, the rapid growth of the North American economy during the post war era managed to shadow the need to import Lean Manufacturing strategies, as competitiveness was still supported mainly by investments, rising demand, and low overseas competition.

Only after the first oil crisis, by the eighties, there was a need in western economies to sustain the industries competitiveness not only with investments, but also with resources, equipment, human capital, and supply chain management. Hayes and Wheelwright's (1984) book is considered to be the turning point of “new” manufacturing strategies as a field of study in the western world, and it is one of the most cited by authors all around the world. As they describe it, the importance of their work is to “*offer a wealth of remedies for American industry's neglect of competitive manufacturing strategies and its resulting loss of productivity*”. Following the example set by world-class manufacturers, they intended to show what American industry had to do in order to regain its “*preeminent spot in the marketplace*” (Hayes and Wheelwright, 1984).

The turn of the century and the accelerated globalization phenomenon created a proper atmosphere for cultural, scientific, technological and academic exchange. In this environment, modern manufacturing strategies began to nurture and complement themselves, gaining relevance worldwide. The term “Lean Manufacturing” (LM) was then coined to embrace a set of strategies and tools aimed at improving productivity and efficiency through a systematic search and elimination of manufacturing waste all along the value chain (Schonberger, 2007).

In 1990, Womack, Jones and Roos published “The machine that changed the world”, telling the story of Lean Production, mostly by means of what is called the Toyota Production System (TPS). One of the most important contributions of their work related to the fact that it objectively compared Lean Manufacturing against mass production, revealing serious weaknesses that the later manifested when dealing with the growing demands of costumers regarding quality, customization and service.

More important, they established the grounds for a Lean Manufacturing “globalization”, analyzing possibilities and cultural barriers in countries such as Mexico, Brazil, South Korea, and Western

Europe. The number of papers published over the matter grew exponentially afterwards, with the topic becoming a must-do for companies around the world due to the impending market and globalization of the late 20th century, and the beginning of the 21st.

Nowadays, Lean Manufacturing continues to be an important trend in the manufacturing industry, constantly evolving in order to adapt to a changing environment. Its importance has been also recognized in other sectors of the economy (Čiarnienė and Vienažindienė, 2014), leading to more "universal" frameworks being referred to as Lean Thinking or Lean Management, aimed at applying LM concepts to maximize efficiency, quality and service in any kind of business, from restaurants, hotels, banks and other service oriented business, to construction, education and even government agencies (Janssen and Estevez, 2013; Leite and Vieira, 2015; Solaimani and Sedighi, 2020).

Even with the renown that Lean Manufacturing has gained worldwide in the past years, concerns have been arising over how it can be implemented in the specific and complex contexts associated with cultural, social, economic and even environmental variables that are endemic to each country or region (Ciccullo et al., 2018; Espejo Alarcón and Moyano Fuentes, 2007; Rahman et al., 2010). More important, how companies and organizations can be sure that their investments in Lean Manufacturing implementation will be returned and maintained as performance improvement, in times when even the performance measurement changes according to context conditions (Büyüközkan et al., 2015; Pham and Thomas, 2011).

Lean Manufacturing faces also another recent challenge due to a growing interest from communities on the secondary and adverse effects of industrial development (Resta et al., 2017; Sonntag, 2000), which, even when revealed some decades before, wasn't take into account among competitive priorities of most industries, or even government agencies. In this way, environmental protection, nonrenewable resource management, communities' wellbeing and their social development began to be seen at the same level of economic performance (Despeisse and Vladimirova, 2014).
In this context, the challenges facing Lean Manufacturing for the coming years will be to address multidimensional performance measurements such as environmental and social impacts and to adapt itself, incorporating new tools and methodologies to be considered as a successful sustainable performance improvement strategy (Piercy and Rich, 2015; Resta et al., 2017; Vinodh et al., 2011).

1.3.2. Lean Manufacturing Principles

Lean manufacturing and high performance manufacturing related literature is rich with principles and values linked to manufacturing philosophies often connected to lean (Shah and Ward, 2003). Nevertheless, managing manufacturing operations is a complex task which encompasses a multi-objective nature. Therefore, pursuing those different objectives might require different approaches, which in turn, can be translated to different principles. In this scenario, it becomes difficult to properly define which of those principles specifically constitute the lean manufacturing concept and which ones are part of other manufacturing philosophies (Čiarnienė and Vienažindienė, 2014).

Liker's (2004) book has become a world know reference regarding lean manufacturing principles, and has been used as a guide by some well-known authors in the field like Bergenwall et al. (2012) and Bhasin and Burcher (2006). It is important however, to mention that Liker's principles are drawn from TPS, which is widely accepted as a predecessor of most lean manufacturing philosophies, but has to be approached with caution when dealing with different kinds of industries, processes and contexts, as it was developed by Toyota specifically for the automotive industry and its supply chain. In spite of this, the TPS principles have been proven to be very versatile, as they are almost seamlessly applicable to all assembled goods industries (Pegels, 1984), and have been used even to improve performance in fields completely different from manufacturing like health care operations (Nelson-Peterson and Leppa, 2007; Ng et al., 2010).

Since Liker's TPS principles have been widely cited in literature, and practitioners recognize them as an important lay ground of lean manufacturing implementation, each one of them, along with a brief description is presented in Table 2. While TPS principles, and LM principles in general, are widely discussed in two seminal books (Liker, 2004; Womack et al., 1990), and are considered in some research works (Bergenwall et al., 2012; Büyüközkan et al., 2015; Manotas Duque and Rivera Cadavid, 2007; Zhou, 2016); companies often struggle with LM implementation (Bhamu et al., 2014) because they lack the commitment to all lean principles as a whole (Bhasin and Burcher, 2006; Hallam and Keating, 2014), and fail to view lean as a non-stopping journey, which requires a deeply embed "lean leadership" culture on all levels of management, but also at shop-floor level, as presented in Figure 4.

Figure 4. Lean leadership principles. *Source: (Dombrowski and Mielke, 2013)*

Corporate culture is often cited as the cause for many failures in lean manufacturing implementation (Bhasin and Burcher, 2006; Dombrowski and Mielke, 2013; Hallam and Keating, 2014; Hines et al., 2004), with Čiarnienė and Vienažindienė (2014) stating that "*only 10 percent or less of the companies succeed in implementing lean manufacturing practices*". This is exacerbated by findings of only 41% of companies strongly agreeing on viewing lean as a fully integrated management philosophy (Zhou, 2016).

In this context, it is possible that some companies fail to fully integrate lean principles into their culture due to context factors (Rahman et al., 2010), and rather try to implement isolated lean practices (Bhasin and Burcher, 2006; Chase, 1999; Ciccullo et al., 2018) with less success due to lack of coherence with the rest of the organizational thinking. Since a successful lean manufacturing implementation requires an adaptation of a company culture (Taleghani, 2010), it might explain why it is widely accepted that it takes between three and five years (Bhasin and Burcher, 2006; Čiarnienė and Vienažindienė, 2014; Hines et al., 2004; Sheridan, 2000).

Table 2. Toyota production system principles

No.	Principle	Description
1	Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals	This principle clearly goes beyond manufacturing management and emphasizes the need to view lean as a culture fully integrated with the company operations. It is almost inevitable that tradeoffs between sales, procurement, and manufacturing priorities need to be done in everyday operations, but from a lean point of view, long-term results and conformance with the other lean principles must dictate decisions at company level, not only at factory floor level (Bhasin, 2008; Hines et al., 2004).
2	Create a continuous process flow to bring problems to the surface	Process flow is considered as a starting point of a successful LM implementation since it brings awareness of problems and wastes (mudas) (Bergenwall et al., 2012). In theory, continuous flow should move items from one operation to another in a smooth way (Khodeir and Othman, 2016; Manotas Duque and Rivera Cadavid, 2007), without creating unnecessary waiting, movements or inventories (Bhasin and Burcher, 2006; Büyüközkan et al., 2015; Čiarnienė and Vienažindienė, 2014), however, in practice, some level of inventory is often maintained in the necessary operations (Bergenwall et al., 2012), implying that what should be pursued is a waste minimization and value maximization, rather than an utopian complete waste elimination.
3	Use “pull” systems to avoid overproduction	A pull approach to supply chain, means that the entire chain is “pulled” from the customer demand, instead of a traditional push approach, where the factory produces in the largest amounts possible, and that production in “pushed” on the market (Manotas Duque and Rivera Cadavid, 2007). A first in-depth comparison between push and pull systems was done by Womack et al. (1990), pointing out on how the traditional push method used by most western (North American and European) car manufacturers excessively stressed the entire supply chain, creating excessive amounts of inventories on each link, increasing the financial burden for manufacturers, suppliers and dealers, and very often, ending up with large stock of un-demanded products, while being short of those that the customers are requiring. A well-established pull system should help reducing overproduction, and therefore inventories and capital. It should also minimize the “bullwhip” effect upstream the supply chain (Chen et al., 2000; Piercy and Rich, 2015). Nevertheless, it requires good coordination and communication with suppliers and customers, and an extensive use of tools such as Kanban (Büyüközkan et al., 2015) and the infrastructure and equipment required for small-lot, more frequent deliveries.
4	Level out the workload	Minimizing overburden to people and equipment, as well as seeking a balanced production schedule is as important as eliminating waste in a LM system (Bergenwall et al., 2012). While companies like Toyota have managed to keep a relatively leveled workload, while still adhering to a demand driven (i.e. pull) system (Liker, 2004), other struggle hard to cope with production levelling (*heijunka*) amongst the highly variability of today’s market demand (Mason-Jones et al., 2000). The apparent trade-off between pull production and leveling production, stress the need to see lean manufacturing principles as a whole management system (Zhou, 2016), as it connects and depends on other principles relating to suppliers and customers presented later. This is where companies begin to struggle when implementing isolated practices like Kanban with some of their suppliers, but not through the complete value chain. In fact, as Bergenwall et al. (2012) found out, American assembly plants use pull systems with their suppliers, but still “push” the finished product to their dealers. This reflects the slow acceptance of LM principles downstream from large manufacturers (Martínez-Jurado and Moyano-Fuentes, 2014).
5	Build a culture of stopping to fix problems, to get quality right the first time	While *heijunka*, is often difficult for companies to put in practice, the “stop until the problem is fixed” culture is more straight-forward in practical terms. Nevertheless, it requires high levels of commitment from the company management (Bhasin and Burcher, 2006), and to the first principle, as pressure to attend customer orders on-time might prompt temporary palliative actions, that are implemented on short-time, to be preferred over definitive, root cause solutions, that might take more time to implement (Čiarnienė and Vienažindienė, 2014).

6	Standardized tasks and processes are the foundation for continuous improvement and employee empowerment	This principle is one of the least addressed in empirical research, yet it is seen by practitioners as a must-do to implement lean manufacturing (Fullerton et al., 2014; Spear and Bowen, 1999). Many companies implementing lean adhere only to the standardization part of the principle, forcing employees to perform tasks always in the same documented and repeatable way. Over time, people might identify and implement improvements to their way of doing things. If the company does not provide a proper environment and encourage workers to suggest those improvements as updates to the standard method, knowledge is often not transferred to other workers (Bergenwall et al., 2012), and with time people may backslide to the old way of doing things (Čiarnienė and Vienažindienė, 2014). Continuous improvement (*kaizen*) is therefore deeply arranged in the culture of advanced lean companies, and highly encouraged and rewarded (Büyüközkan et al., 2015; Vinodh et al., 2011; Zhou, 2016).
7	Use visual control so no problems are hidden	Practices and tools related to visual controls (like 5S) are amongst the first implemented by companies pursuing lean manufacturing (Bergenwall et al., 2012). Lean companies should encourage employees to make the organization aware of problems (Liker, 2004; Womack et al., 1990; Zhou, 2016), instead of hiding them because of being worried of getting reproached. While the original approach of the TPS to visual controls emphasizes to keep relevant information visible, it also stresses the need to keep it simple and short to make it easily understandable and less confusing. Nevertheless, it has been found on some manufacturing plants, that lengthy information is often displayed prompting employees to be distracted (Bergenwall et al., 2012) and even confused by it.
8	Use only reliable, thoroughly tested technology that serves your people and process	According to this principle, technology should be used to support people in doing their work easy and efficient as possible, and not the other way around. Yet, the adoption of intricate technologies often pose people focus in support of those technologies, requiring even additional and complex tasks (Bergenwall et al., 2012). Pilot plants used as test-beds for new technologies are common practice in line with this principle. They provide an environment for problem solving and improvement of frequent issues that are common in new equipment, without traumatizing daily operations. When technology is proven and refined, it is then implemented in large scale to the productive operation. As with almost all principles, it depends on the management commitment to the first principle (Bhasin and Burcher, 2006), since new technology investments are often decided on their cost-saving potential and therefore, pressure builds on implementing them quickly to profit from those savings, even at the expense of upsetting and costly disruptions to normal production.
9	Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others	Principles 9, 10 and 11, are considered by Pakdil and Leonard (2014) one of two main pillars of the TPS, under the “respect and develop people and partners” category. The other pillar is continuous improvement, which nevertheless requires leadership. Cultural requirements of any company willing to implement LM include the promotion of “lean” leaders at all levels, that are flexible to adapt to changes, “live” the LM philosophy, and serve as multipliers of it all along the organization (Bhasin and Burcher, 2006; Čiarnienė and Vienažindienė, 2014; Comm and Mathaisel, 2005). Lean leaders can be found on all stages of the value chain (from supply to sales) and at all levels of the organizational hierarchy, since lean principles does not differentiate between the traditional white and blue-collar separation of workforce (Dombrowski and Mielke, 2013).
10	Develop exceptional people and teams who follow your company’s philosophy	Like in the precedent principle, people is always on the focus of TPS. Encouraging people of giving the best of them, while feeling comfortable in expressing their ideas and concerns, creates an environment for learning, teamwork and continuous improvement (Büyüközkan et al., 2015; Martínez-Jurado and Moyano-Fuentes, 2014). Nevertheless, human factors are among the most documented causes of unsuccessful LM implementations (Shah and Ward, 2003; Spear and Bowen, 1999; Taggart and Kienhöfer, 2013), however they often relate to insufficient management commitment, poor communication and organizational culture (Čiarnienė and Vienažindienė, 2014; Gobinath et al., 2015).
11	Respect your extended network of partners and suppliers by challenging them and helping them improve	The concept of people respect under the TPS goes beyond the internal social outcomes (i.e. the employees), to external outcomes, including a broader reach of the surrounding society that is affected (positively or negatively) by the company operations (Liker, 2004). Lean principles spread all across the value chain. Downstream to the customer, and upstream to suppliers (Martínez-Jurado and Moyano-Fuentes, 2014), which are viewed as partners and an

		integral part of the company success, therefore, are expected to adhere to the same principles. Rather than continuously seeking for alternate suppliers that offer the same product for a lower price, TPS values the cost of learning associated with developing a new supplier. This makes becoming a “lean” supplier difficult to achieve, as the number of tier 1 suppliers of a lean company is by principle small (Pakdil and Leonard, 2014). In the meantime it provides a certain degree of stability since the company provides a long term commitment to obtain a return of their investment (not necessarily financial, but often as technology, development, and consultancy) on the supplier (Bhasin and Burcher, 2006; Hines et al., 2004).
12	Go and see for yourself to thoroughly understand the situation	In lean manufacturing, everything starts on the plant-floor (G*emba*) (Dombrowski and Mielke, 2013). Under a lean management philosophy, this can extend to every place of the value chain where value is being added (e.g. the counter on a bank or service operation, the E.R. on a hospital, the shop-floor on a sales operation). Every management philosophy goes down to the decision-making process, and in the TPS case, decisions must be taken in an informed way, which can only be achieved when a full comprehension not only of a problem, but of the entire process around it, is complete (Dombrowski and Mielke, 2013). Gaining full understanding of a situation (a problem or an improvement opportunity) requires not only getting immerse on the situation and “seeing it for yourself” (*genchi genbutsu*), but also to receive the feedback and viewpoints of the people that has been involved in the process (Liker, 2004). The decision-making after the complete picture has been taken should be more effective, but it also needs the input from everyone involved in the process to be successful, as it is reinforced by the next principle.
13	Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly	Companies adhering to TPS principles might seem slow-moving under this principle. However, evidence shows that in the long-term, a slow approach to a solution-finding process, but a fast implementation of it, is faster than a quick solution that might require a continuous effort to improve “on the run” as previously unconsidered flaws emerge under its implementation (Liker, 2004). The prevailing culture in many companies is that highly ranked executives should prove their value by making fast decisions on their own. Culture on lean companies does not take away the responsibility from senior executives and department managers, but encourages them to make decisions considering all company levels (Bhasin and Burcher, 2006; Dombrowski and Mielke, 2013). This process can be time-consuming, but it will also assure that all points of view were considered, and that consensus has been achieved between the people taking the decision and the people that will be affected by it, therefore providing a smoother implementation.
14	Become a learning organization through relentless reflection and continuous improvement	This principle acts as a summary of al preceding principles, and also of the two pillars (Pakdil and Leonard, 2014) of TPS, continuous improvement and respect for people. Continuous improvement is often related in different definitions of LM, with more than 90% of companies with some level of lean adoption agreeing that it is directly related to the lean concept (Zhou, 2016). Learning derived from continuous improvement processes can be considered as one of the most significant asset for any company (Spear and Bowen, 1999). In some cases, continuous improvement has evolved as a “pursue of perfection” philosophy, which is strongly based on all TPS principles. As Čiarnienė and Vienažindienė (2014) point out: *“perfection requires constant striving to meet customer needs and improve process with zero defects. Creating flow and pull starts with radically reorganizing individual process steps, but the gains become truly significant as the entire steps link together. As this happens more and more layers of waste become visible and the process continues towards the theoretical end-point of perfection, where every asset and every action adds value for the end customer. It is the conviction that improvement efforts are never finished, and it is the consistency to keep the discipline for improvement in place”*.

1.3.3. Lean Manufacturing Practices and Tools

As mentioned in past sections, Lean Manufacturing origins can be traced to a series of quality and continuous improvement focused tools, but also to a manufacturing philosophy based mostly on principles from eastern culture. That division of viewpoints has marked lean manufacturing research since its beginnings (Abobakr and Abdel-Kader, 2017). Some authors argue that principles are the base of lean manufacturing (or even any manufacturing strategy) as they dictate the path for achieving the desired goals (Bergenwall et al., 2012; Čiarnienė and Vienažindienė, 2014; Hallam and Keating, 2014; Liker, 2004; Schonberger, 1996), and tools need to be selected according to how they align with those given principles.

While principles rely on culture, and lean manufacturing viewed as a philosophy relies on both of them, it is often difficult to put those principles on practice. That's why, a series of lean manufacturing practices and tools have been developed over time. Each company then choses which practices to implement as a reflect of the principles it has adopted in its culture (Abobakr and Abdel-Kader, 2017; Shah and Ward, 2003). This approach is widely adopted in industry (Zhou, 2016), and in research, many of the most cited research done to date approaches lean as a series of tools or practices (Bortolotti, Danese, et al., 2015; Dal Pont et al., 2008; Furlan et al., 2011; Shah and Ward, 2003).

The level of adoption of a given practice or tool is more easily measured than principles or culture, as it reflects on the execution of well-defined activities rather than on philosophical concerns. This explain why empirical, survey based, research is more fond to the practices (and tool bundles) approach, due to quantifying reasons, while LM principles related research is found in case studies (Bergenwall et al., 2012; Büyüközkan et al., 2015). The "bundles" approach (i.e. sets of LM practices and tools interrelated to each other) was proposed by Shah and Ward (2003), with four original bundles: TQM, TPM, HRM, and JIT.

Practices encompassed in the JIT bundle are aimed at producing the right product at the right time (Womack et al., 1990), therefore reducing inventories, lead times, and evidencing "*mudas*" (waste). TPM practices focus on achieving the highest efficiency rates from equipment and assets (Belekoukias et al., 2014), therefore improving production rates and decreasing downtimes mostly through predictive and preventive maintenance. Statistical methods and continuous improvement are the base grounds of TQM practices (Shah and Ward, 2003), which aim to exceed the customer quality expectations in a proactive way (i.e. assuring the process conditions that lead to a good product, instead of controlling the product quality after it was manufactured). Finally, HRM practices are related to the engagement of the workforce in the lean process (Bortolotti, Danese, et al., 2015) and the strengthening of organizational capabilities (Vivares-Vergara et al., 2016) through empowerment, problem solving, and communication.

In the past decade however, the four bundles approach, has evolved to include new practices and goals according to new trends in management, markets, and technology. New bundles such as VSM and KAIZEN have been recognized in recent works (Belekoukias et al., 2014; Bhamu et al., 2014; Ruben et al., 2018; Vinodh and Vimal, 2012), and although they might embrace practices originally included in the four bundles, they differ in their specific focus. For example, VSM gather practices oriented towards material and information flow mapping (Abobakr and Abdel-Kader, 2017), but also aims at eliminating non-value-added activities that ca be considered as wastes. Table 3 presents LM methods and tools derived from literature along with their commonly related bundles. As the table shows, many practices are present in different bundles, which is a common problem when LM implementation is addressed from a purely tools/bundles approach, since tools and practices can complement different principles and help achieving different goals, but instead, companies can end up implementing a single set of practices in an isolated and independent manner (Čiarnienė and Vienažindienė, 2014).

This tool implementation based approach is however criticized, and even mentioned as one of the barriers for getting the expected results from LM implementation (Abobakr and Abdel-Kader, 2017). Spear and Bowen (1999) claim that the difficulty for companies dealing with TPS "*is that observers confuse the tools and practices they see on their plant visits with the system itself*". This makes sense in a practical way since a tool is something designed to perform a specific task, however it won't perform the task by itself, and buying (or implementing) a tool won't necessarily guarantee that the user (the company) is capable of using it, or even that it is the proper or most efficient tool for the job (Bergenwall et al., 2012). Since every company have different problems and necessities, instead of pushing a set of standard, pre-defined, tools through its operating system, it is better to design a comprehensive system that satisfies the base principles and uses the tools that support it (Lander and Liker, 2007).

Table 3. Lean manufacturing practices and tools

	Lean Bundles					
	JIT	**TPM**	**TQM**	**HRM**	**VSM**	**KAIZEN**
Lean Practices and Tools	One-piece flow Pull systems Takt time Cell manufacturing Levelled production Kanban Visual controls JIT purchasing Lot size reduction Cycle time reduction SMED Bottleneck removal Flow oriented layout Limited WIP inventory Automated tools	OEE SMED 5S Autonomous maintenance Quality maintenance Predictive maintenance Preventive maintenance Planning and scheduling Critical machines and spares Standardization of components	Poka-yoke Visual control Andon Full work system Benchmarking Quality management Card systems Process capability Continuous improvement SPC Process feedback Supplier quality involvement Customer quality involvement APQP Quality management systems	Self-directed work teams Cross functional workforce Small group problem-solving Employee suggestions Employee empowerment Smooth communication Knowledge management Standardized training	Current state map Future state map Flow diagrams Standardized work sheets Waste identification Waste minimization Material and information flow Process mapping	Brainstorming Continuous flow 5S Five whys Pareto chart Gant chart Process map Bottleneck removal Employee suggestions Continuous improvement Inventory reduction

Own elaboration based on: (Abobakr and Abdel-Kader, 2017; Belekoukias et al., 2014; Bortolotti, Danese, et al., 2015; Narayanamurthy and Gurumurthy, 2016a; Ruben et al., 2018; Shah and Ward, 2003; Vinodh and Vimal, 2012; Zhou, 2016)

Figure 5 presents a proposed pyramid, or sand-cone, for lean manufacturing implementation. It draws from previously exposed and supported concepts, as well as the work of Koufteros et al. (2007) and Azuan et al. (2017). Organizational culture is placed at the bottom, since any tool, practice, or principle that is implemented won't last if it goes against the prevailing culture (Bhamu et al., 2014). Principles nurture from the culture as they represent a more tangible "rule book" that guide the company decision-making, and how it reacts to different situations. Practices come on top of principles in a think-act manner (principles dictate the way the company thinks, and it acts through different practices) (Koufteros et al., 2007). Finally, tools become the mechanism that dictate how tasks are specifically performed.

Since the way tasks are performed, and the problems associated to them changes frequently, LM tools evolve and need to be replaced or adapted once they are no longer as effective as the new tools available (Souza et al., 2018). The same happens with practices when important changes are given in a company strategy, technology, processes, products or markets (Koufteros et al., 2007). These changes are however less frequent; therefore, practices are adjusted less often than tools. At the bottom of the pyramid, changes are very seldom and very difficult to achieve. A change of operating principles will probably require a complete change of the company strategy (Losonci et al., 2017), while a cultural change might take several years and even a generational change in management. As tools are more easily changed, it can be argued that they can be adapted to achieve the desired success of LM, while an appropriate culture that supports the LM principles is more difficult to put in place, therefore more determinant of LM success (Hallam and Keating, 2014; Zhou, 2016).

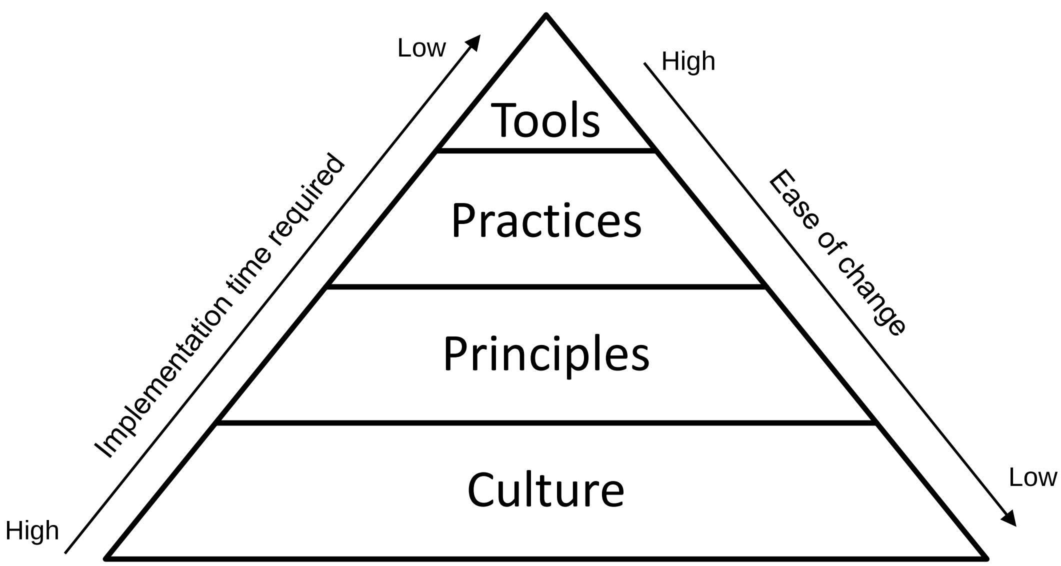

Figure 5. Lean manufacturing implementation pyramid. *Own elaboration, based on: (Azuan et al., 2017; Koufteros et al., 2007; Schein, 2010)*

1.4. Sustainability

During the second half the 20th century, the world economy experimented a steady growth. Available resources (economic, raw materials, labor force, energy, etc.) to sustain that growth were hardly scarce. In this way, economic growth was vastly supported by the exploitation, consumption, and transformation of those resources, knowing that (perhaps without conscience), there was a limited amount of them available in the long term.

With the accelerated growth in world population (see Figure 6), the per-capita non-renewable resources available diminish proportionally (Jayal et al., 2010). For the first time, during the eighties, humanity faced a global shortage in resource availability, which, in addition to the beginning of globalization, started to produce a significant impact on world's economy. Indeed, in 1987 the World Commission for Environment and Development defined the concept of sustainability as

"*…development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Pereira et al., 2011).

In spite of a conscience call to the industry during the nineties towards the importance of environmental sustainability and social responsibility afterwards, there is little evidence that can prove that, at least until the end of the 20th century, companies and organizations gave enough relevance to them among their other competitive priorities (Porter and van der Linde, 1995). Although for Whittaker (1999), by the turn of the millennium the situation was beginning to look more promising in light of private and public initiatives developed worldwide through the World Business Council for Sustainable Development (WBCSD), and the fact that by then, around 2000 of the world leading companies had signed the International Chamber of Commerce's (ICC) business charter for sustainable development.

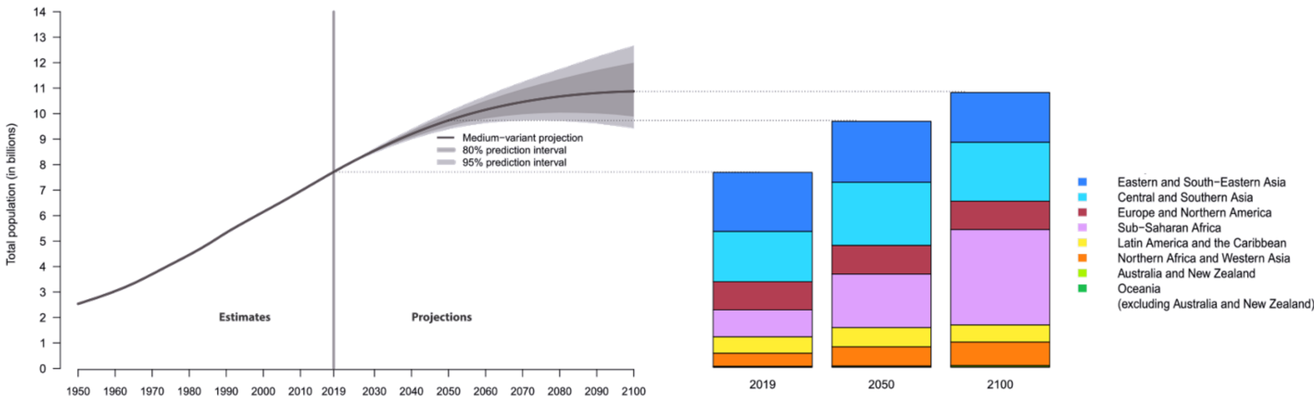

Figure 6. Evolution and forecast of world population. *Source: (UN Population Division, World Population Prospects: The 2019 Revision, 2019)*

Many authors (Abdul-Rashid et al., 2017; Carter and Rogers, 2008; Despeisse and Vladimirova, 2014; Martins et al., 2011; Ocampo and Estanislao-Clark, 2014; Seuring and Müller, 2008; Slaper and Hall, 2011; Souza et al., 2018; Taticchi et al., 2013) cite Elkington's (1998, 1994) publications as the start point for the conceptual framework of sustainability application and measurement in industries and organizations. Elkington calls this framework "Triple Bottom Line" (TBL) and urges companies to measure their performance through a multidimensional optic, that integrates not only the traditional indexes as profit, return on investment or share value (financial and economic), but also environmental and social aspects.

Studies conducted by Elkington and his co-workers' group (SustainAbility), mainly in North America and Western Europe, reveal that companies face the possibility to fail in the medium and long term if they do not give the required level of attention to social and environmental perspectives, given the growing pressure from consumers, along with government ordinances and laws. They state: *"future market success will often depend on an individual company's (or entire value chain's) ability to simultaneously satisfy not just the traditional bottom line of profitability but also two emergent bottom lines: one focusing on the environmental quality, the other on social justice"* (Elkington, 1998).

Around the beginning of the 21st century, public attention was turned to a multidimensional performance perspective. However, increased visibility came from events, incidents or even accidents widely publicized around the globe. Those events tended to escape public attention after some years (or months), thus, turning away general interest in sustainable performance related matters. This cyclic behavior is shown in Figure 7, where some milestones that led companies and governments to include social and environmental topics in their agendas are presented (Elkington, 2013).

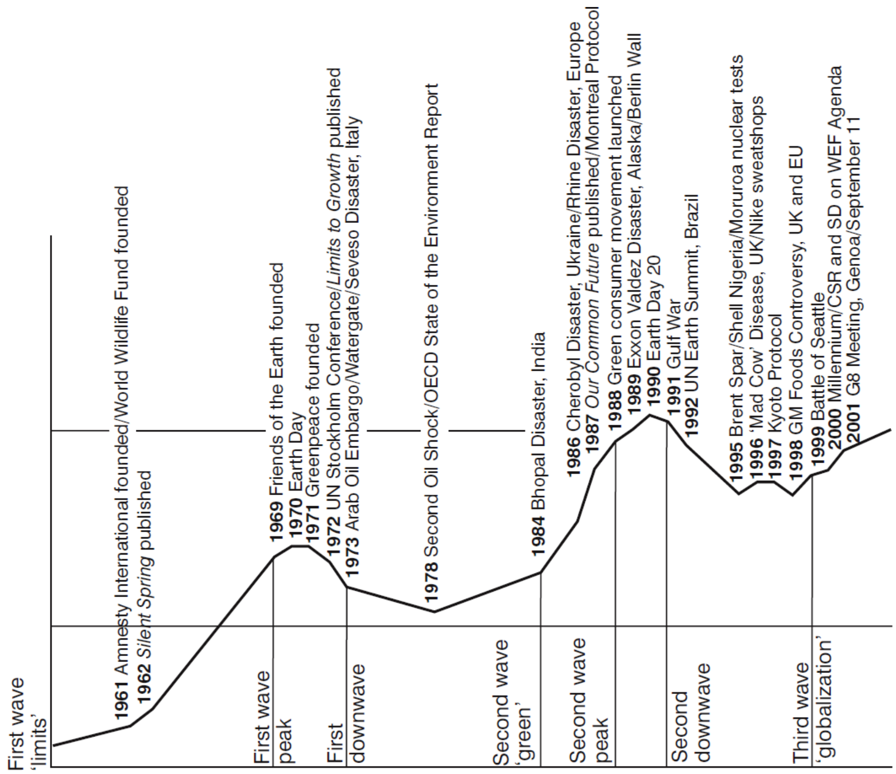

Figure 7. Corporate Social Responsibility (CSR) and Sustainable Development (SD) frequency of mentions in literature. *Source: (Elkington, 2004)*

It is expected that in the 21st century, those cycles or "interest waves" (Figure 7) keep a growing trend, with shorter frequencies, but also with lower downturns. Nevertheless, it is important to notice that in the academic community, interest has been growing with a faster trend (Slaper and Hall, 2011), up to the point where social (and environmental, if applies) impact valuation has become a must in almost every research, especially those regarding business and industrial activities (Souza et al., 2018).

Another sustainability issue has raised around globalization. This phenomenon has rapidly increased competition for markets between developed and developing countries, with growing concern for environmental and social consequences derived from operating in countries with regulatory laxity on those matters (Busse, 2016; Distelhorst et al., 2017; Zhang et al., 2017). Different stakeholders including consumers, communities, governments and NGOs are also increasing pressure for more responsible ways of production and consumption (Jacobs et al., 2016; Jonkutė and Staniškis, 2016).

The sustainable operations management is a relatively new paradigm. It was first addressed by Kleindorfer et al. (2005), who recognized that people (employees and those external to companies) and environment are important elements of long-term success of companies, in the same way as profitability. Therefore, they propose that sustainable OM should integrate "*the profit and efficiency orientation of traditional OM with broader considerations of the company's internal and external stakeholders and its environmental impact*" (Kleindorfer et al., 2005). More interestingly to this research, Kleindorfer et al. (2005) considered that one key area of integration of the TBL concept in OM was "Lean and green OM".

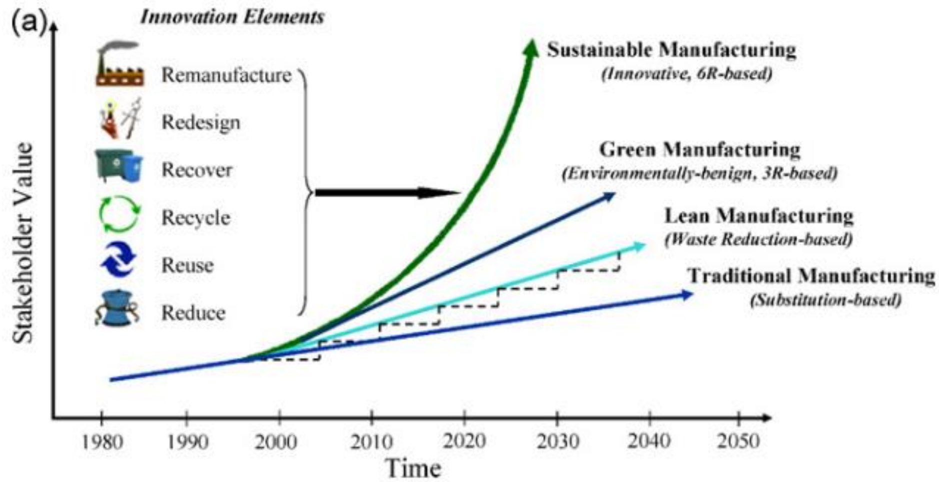

Figure 8. Expected evolution of sustainable manufacturing paradigms. *Source: (Jayal et al., 2010)*

The work of Kleindorfer et al. (2005) marked a turn point in the rapid development of new theories, paradigms and frameworks for the integration of sustainability in different branches of OM. This field has been enhanced ever since by important contributions such as Linton et al. (2007), Seuring and Müller (2008), Pagell and Wu (2009), and more recently, Pagell and Shevchenko (2014). However, those contributions have been made mainly from the supply chain perspective, significantly boosting the sustainable supply chain management paradigm, while the sustainable manufacturing, and particularly, the integration of lean manufacturing with sustainability, topic has somehow been lagging behind (Jayal et al., 2010). In fact, Jayal et al. (2010) defined manufacturing as the "core operation in a product's supply chain", and therefore emphasized on the need to include sustainability elements in manufacturing processes similarly to how they were being incorporated in supply chain management. Their expected evolution of manufacturing paradigms from conventional manufacturing to sustainable manufacturing (including lean manufacturing) is presented in Figure 8.

1.5. Sustainable Performance

Traditional sustainability definitions are difficult for companies to implement in their day-to-day decision making process (Zhang et al., 2017), and therefore to translate them in to goals and performance measures that can be monitored, and improved. This happens because managers struggle to cope with definitions that are too "abstract" and goals that are too far down the horizon (like *"the needs of future generations"*), and are pressed to show short-term results especially regarding financial outcomes (Sutherland et al., 2016).

In this environment, setting (and more importantly, reaching) sustainable performance goals becomes a challenging issue for manufacturers, as there is no consensus about the desirable level of sustainability that a company should achieve and goals are often conflicting between internal and external stakeholders (Besiou and Van Wassenhove, 2015). Therefore, alternative frameworks like sustainable responsible manufacturing (Jonkutė and Staniškis, 2016), fit manufacturing (Pham and Thomas, 2011), and the triple bottom line, emerge as alternatives to make sustainability operationalization more affordable to decision makers.

Organizational performance measure from a tridimensional approach, as proposed by the TBL perspective is often known as the 3P's: Profit (economic), People (social) and Planet (environmental). Although there is no universal standard for calculating TBL performance (Gong et al., 2018; Jayal et al., 2010), there are several measures and indexes used for calculating each one of the three pillars. However, depending on the field of application, some measures are more suitable than others, as the TBL concept can be applied to all kind of organizations from government agencies and policies, to manufacturing or service industries (Slaper and Hall, 2011).

Table 4 presents an overview of how general operational, environmental and social performance metrics, that have been employed jointly in OM literature, have evolved in the past ten years, leading to more comprehensive models, that, nevertheless, unlike traditional operational and economic metrics (OEE, cost, quality, delivery, service, ROI, EBITDA, etc.), still lack their overall applicability and comparability. Therefore, "*continued research is required on the characterization of sustainability metrics for manufacturing processes to achieve truly sustainable manufacturing technologies*" (Reich-Weiser et al., 2008), a notion enforced by Jayal et al. (2010) concluding that "*one of the major challenges in developing such models is the lack of metrics to quantify the extent of environmental and societal impacts on supply chain operations*", and even more recently by the works of Ben Ruben et al. (2017) and Gong et al. (2018).

Academic literature dealing with sustainable performance in operations management mainly consist of frameworks either for developing strategies to account for sustainability in manufacturing and operations (Despeisse and Vladimirova, 2014; Kowang et al., 2016; Longoni et al., 2014; Longoni and Cagliano, 2015; Martínez León and Calvo-Amodio, 2017; Ocampo and Estanislao-Clark, 2014; Pham and Thomas, 2011), or presenting sustainable performance metrics and ways to assess the sustainability of a given organization or parts of its value chain (Gimenez et al., 2012; Gualandris et al., 2014; Ketokivi and Schroeder, 2004; Reich-Weiser et al., 2008).

In both cases it is important to consider that the concept of sustainability is approached from different perspectives in the literature. One perspective adheres to the TBL approach accounting for some level of balance between the three pillars (economic, environmental, and social) while, in other cases, sustainability is referred to as the ability of an organization to "sustain" itself on the long-term (Nordin and Belal, 2017; Pham and Thomas, 2011; Reich-Weiser et al., 2008). This cannot only be related to economic, social and environmental drivers (Gualandris and Kalchschmidt, 2016; Pagell and Wu, 2009), but also is related to sustained growth through time, from a purely financial point of view (Friedman, 1970; Kowang et al., 2016).

Practices oriented to improve sustainability can be applied to all links of the value chain (supply, manufacturing or sales), thus companies must account for the multidimensional nature of performance to properly understand how it is affected by different practices (Ketokivi and Schroeder, 2004). From this perspective, Despeisse and Vladimirova (2014) urge manufacturers to consider non-financial information (environmental and social impacts) in their decision-making processes, but acknowledge that this is rarely done due to the difficulties of evaluating qualitative benefits and the inconvenience of comparing those to short term economic benefits. This makes integration of sustainability into their day to day operation a struggle (Longoni and Cagliano, 2015). Said vision is shared by Ocampo and Estanislao-Clark (2014), as they claim that firms are often uncertain about investing in sustainable manufacturing practices due to the "intangible" nature of their outcomes .

Table 4. Operational, environmental and social performance metrics

Authors	Operational performance	Environmental performance	Social performance
Reich-Weiser et al. (2008)	Cost, quality, return on investment (ROI)	Use of resources: coal, oil, water, energy Environmental impact: pollution, toxicity, climate change	Poverty, gender equality, nutrition, child mortality, sanitation, health, education, housing, crime, employment
Slaper and Hall (2011)	Incomes (sales), job growth, revenue	Sales dollars per KWh, greenhouse gas emissions, use of recycled material, water consumption, waste to landfill, land use.	Training hours per employee, welfare, career retention, charitable contributions, safety incidents rate, job growth.
Gimenez et al. (2012)	Production and operational costs	Energy use, resource use, operations footprint, waste reduction, pollution reduction, emissions reduction, hazardous/harmful/toxic materials use, environmental accidents.	Equitable opportunities, diversity encouraging, community connection, quality of life, democratic processes, accountable governance structures
Silva et al. (2013)	Cost, manufacturing time, materials consumption	Energy consumption	Work environment, employee satisfaction
Gualandris et al. (2014)	Not considered	Biodiversity, air and water pollution, energy, recycling	Working conditions: health and safety, training Human rights: child labor, discrimination
Longoni et al. (2014); Longoni and Cagliano (2015)	Cost, delivery, flexibility, quality	Pollution, resource consumption, emissions generation, degradation of ecosystem	External (community): social reputation, life quality Internal (workforce): employee satisfaction, creation of skills, health
Piercy and Rich (2015)	Cost, service, quality, waste reduction, productivity	Pollution, emissions, materials used, energy use, emissions from transportation, use of recycled materials, recycling	Workforce: safe working environment, good working conditions, fair wages and payment, non-discrimination, union relations Community: charitable donations, community support
Vinodh et al. (2016)	Value-added time, value-added cost, raw material consumption, power consumption	Carbon footprint, water eutrophication, air acidification, water consumption	Physical load, work environment risks, noise level
Resta et al. (2016)	Generated economic value, distributed economic value, retained economic value	Resource use, Emission to air, Emission to water, Emission to land	Employment, labor/management relations, health & safety, training, diversity and equal opportunity, remuneration, grievance mechanisms
Helleno et al. (2017)	Operation cost, effective cost, stock cost	Power consumption, water consumption, harmful gases release, waste segregation, waste with traceable treatment, green production rate, environmental management system	Absenteeism, turnover, accident rate, noise level, national production, benefits and commissions
Gong et al. (2018)	Costs, revenues, profit sharing, sustainable value	Emission reduction, natural resources usage, energy efficiency, waste reduction, material disposal, use of recycled materials, environmental supplier criteria	Local jobs, human rights, training, health care and safety, purchasing localization, labor equity, community support

This difficulty of translating environmental performance and social performance into indexes comparable in economic or financial terms to operational performance creates a challenge for companies and managers, as they need to justify those initiatives to shareholders. Some social and environmental initiatives, safety measures and pollution control mechanisms, can increase the manufacturing cost (or manufacturing time), thus having negative short-term effects on operational performance (Gimenez et al., 2012), and creating the need to find better means to improve environmental and social performance (Gualandris et al., 2014; Ketokivi and Schroeder, 2004).

As a way to achieve long-term business sustainability, Pham and Thomas (2011) propose the “Fit Manufacturing Framework” (FMF), which combines lean, agility, and sustainability principles to develop a more robust manufacturing strategy that is able to cope with constant changes in the market. However, in this framework, sustainability is defined as "*being able to attain long-term profitability in what is now an increasingly volatile and complex marketplace*", which does not necessarily mean having acceptable environmental and social performance.

As presented in Figure 9, the FMF starts with business and manufacturing strategy, sales, financial and knowledge development. Those items are called the core systems, and they create the bases for operational systems development, which comprises elements of lean, agility (linked mostly with flexibility), and sustainability (related not only to the strategy, but also to external factors that might affect the core system). Finally, business systems are developed on top of the other two, and comprise the technological aids, demand and supply chain management, and the re-configurability of systems needed to respond to the changing environment (Pham and Thomas, 2011).

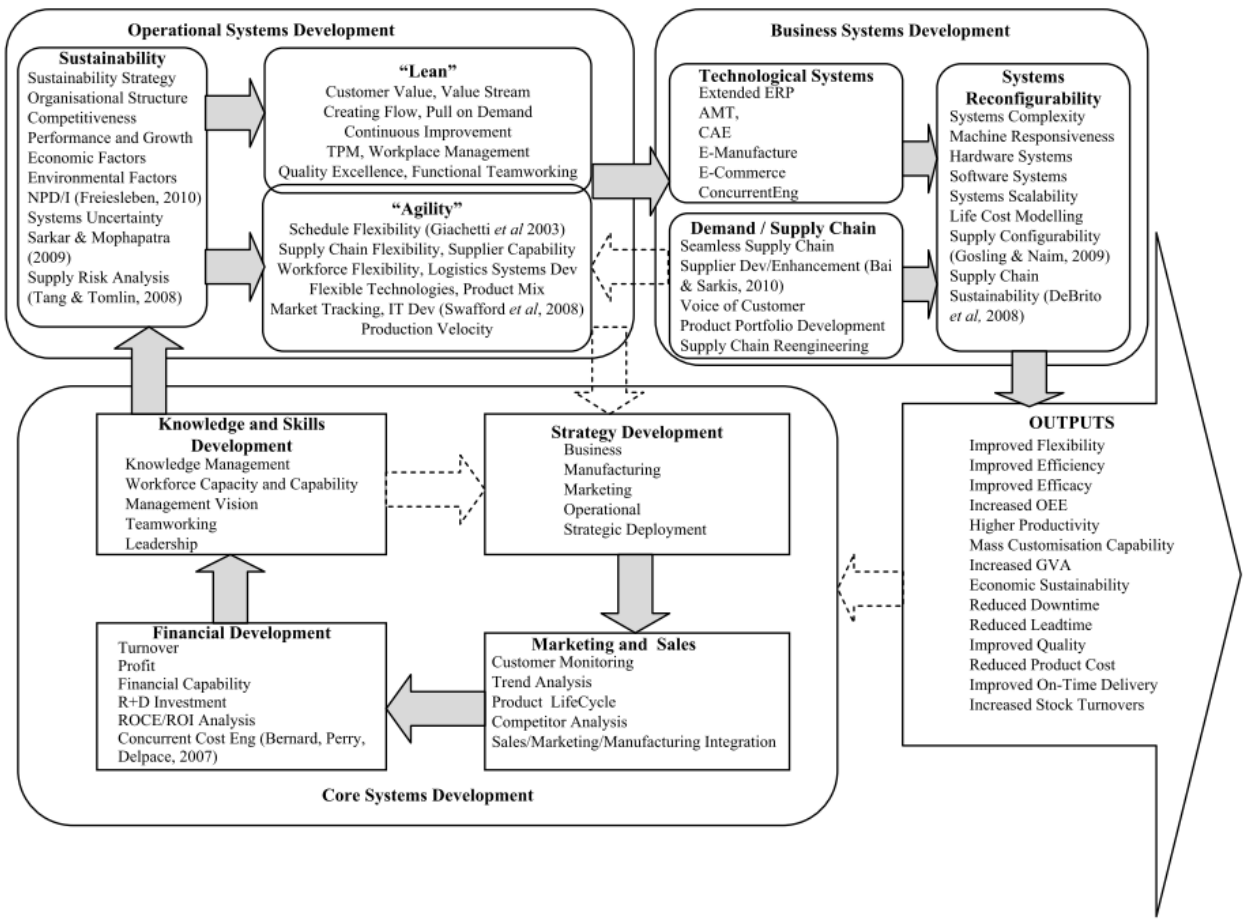

Figure 9. Fit Manufacturing Framework (FMF). *Source: (Pham and Thomas, 2011)*

The FMF outputs should then reflect improved flexibility, improved efficiency, improved efficacy, increased OEE, higher productivity, mass customization capability, increased GVA, economic sustainability, reduced downtime, reduced lead-time, improved quality, reduced product cost, improved on-time delivery and increased stock turnovers. According to Pham and Thomas (2011), those elements should allow for long-term profitable sustainability. That, however, is not necessarily supported by all three TBL pillars as previously evidenced.

Longoni et al. (2014), and Longoni and Cagliano (2015) present a different approach to adopting sustainable performance drivers in organizations. In their first study, they suggest that some HRM practices can lay the foundation for sustainability, while acknowledging that more research is still required on linking operational practices (which include LM) to social and environmental dimensions. Their findings show that HRM practices (training, involvement and incentives) have a direct impact on SP as they improve employee satisfaction, health and safety. In addition, training and teamwork have positive impacts on EP since they provide the capabilities and commitment needed to address environmental problems. Their second investigation discusses the integration of sustainability (environmental and social) into the competitive priorities of different operations strategy configuration models (price oriented, market oriented and innovation oriented). Their findings suggest that environmental and social priorities are less highly regarded by price-oriented models since they compete focused on cost and quality, while market-oriented models give more importance to those priorities. Innovation-oriented models show more commitment to social and environmental sustainability, as they compete by differentiation.

Finally, Another interesting framework for LM and sustainability integration is proposed by Martínez León and Calvo-Amodio (2017). They acknowledge that this integration is neither trivial nor straightforward, however suggest six propositions to help overcome those difficulties. Their propositions are derived from conclusions of past works (some reviewed in this paper). Propositions one and two focus on the mix and alignment required between lean and sustainability practices. Propositions three and four relate closely to the environmental perspective calling for the introduction of responsible resource management in lean practices, and a systemic approach between lean (especially supply related) and environmental practices. Finally, proposition five emphasizes the importance of the human component in lean and sustainability, while proposition six focus on the need to approach LM implementation in a systematic and structured way.

1.5.1. Operational performance

The concept of TBL is sometimes addressed as the “3P’s” (i.e. people, planet, profits) (Elkington, 2013). This leads to considering economic performance as one of the pillars of sustainability in organizations, which can be measured by means of money flow (Slaper and Hall, 2011). This notion is widely accepted and several indicators are of common use in industries for measuring their economic, financial or business performance, like profits, return on investments (ROI), return on assets (ROA), earnings before interest, taxes and amortization (EBITDA), and market share, among many others (Büyüközkan et al., 2015; Negrão et al., 2017). In a more general sense, economic variables are also related to income and expenditures, taxes, business climate, and market growth, among others (Gimenez et al., 2012; Slaper and Hall, 2011).

Business performance is nevertheless affected by different aspects that can be both internal or external to a company (Ghalehkhondabi, 2017). In manufacturing operations, it can be said that business performance is a result of operational (or manufacturing) performance, market performance, and financial performance (Avella and Vázquez-Bustelo, 2010; Busse, 2016; Büyüközkan et al., 2015). It is also important to mention that the manufacturing strategy, and subsequently its outcomes, are essential to support a company business (or corporate) strategy (Vivares-Vergara et al., 2016).

Studies have provided evidence that a strong performance in operational measures such as cost, quality, delivery, lead time or flexibility can have a positive effect in business performance dimensions (Arcidiacono et al., 2016; Avella and Vázquez-Bustelo, 2010; Martínez León and Calvo-Amodio, 2017). However, as previously mentioned, financial and market variables (some of them being external to the company) also play a significant effect in a company overall economic performance. This can lead to the scenarios where non-manufacturing related factors such as demand uncertainty, insufficient advertising, negative corporate image, or inadequate distribution channels, among many others, can negatively affect business and economic performance, even beyond strong internal operational outcomes like lead times, inventory levels, quality, etc. (Ghalehkhondabi, 2017).

Therefore, when dealing with manufacturing operations, and especially when considering the adoption of any manufacturing strategy or individual practices such as lean manufacturing, it is important to notice that these strategies are likely to affect business (or economic) performance through improved operational performance (Büyüközkan et al., 2015; Negrão et al., 2017). On the other hand, if one aims to evaluate the effectiveness of a given manufacturing practice or strategy on company performance, it can be argued that performance measuring at operational level can provide direct effects, while measuring performance at business level can be affected by indirect effects from market and financial dimensions. This could explain why it has been found that long-term adopters of LM tend to enjoy better business performance returns than lean newcomers (Agus and Iteng, 2013), as some time is needed for the initial operational improvements (cost, quality, delivery, etc.) obtained from LM to materialize into the market and financial drivers.

Regarding lean manufacturing, it is widely supported that it helps to improve business performance as a consequence of improved operational performance in areas like cost, lead time, cycle time, and waste reduction, and better quality (Thanki et al., 2016). This manufacturing competences, along with flexibility have been found to contribute to business performance also by Avella and Vázquez-Bustelo (2010) and Büyüközkan et al. (2015). On the other hand, evidence gathered from literature by Negrão et al. (2017), shows how some LM practices like HRM and Kaizen are positively related to operational performance measures, but at the same time, negatively related (in some cases) to financial performance measures like ROI and profitability.

As a consequence from the discussion presented in the last paragraphs, when OM research has to deal with the manufacturing system (as it is the case of the present research) effects on TBL performance, without considering external (i.e. market and financial) variables, operational performance can be considered as one of the three sustainability pillars (Gong et al., 2018), which is directly affected by the decision-making processes related to the manufacturing strategy.

Following the same principle, most internal environmental (Negrão et al., 2017) and social outcomes can be also considered as a direct effect of manufacturing. Otherwise, if performance is measured directly at business or economic dimension, results can become heavily biased from other variables not related to manufacturing, and from the time lag between LM implementation and the performance improvement perception from a purely economic or financial point of view (Abolhassani et al., 2016; Helleno et al., 2017; Martínez León and Calvo-Amodio, 2017; Maskell et al., 2011). This argument is supported by Negrão et al. (2017) warning of "*the need for costing/accounting adaptation to traditional systems which have difficulty in accounting for the effects of improvement programs*".

1.5.2. Environmental performance

The second half of the twentieth century was market by an increasing awareness around the exploitation of nonrenewable resources and environmental effects of human activities, especially industrial and commercial (Elkington, 2013). Nevertheless, concrete actions towards reducing the environmental footprint of manufacturing activities where only scarcely approached by companies until the late twentieth century (Campos et al., 2015; Whittaker, 1999).

With growing pressure from different stakeholders, environmental protection has gained relevance in the past three decades, urging companies to reduce their ecological footprint (Garza-Reyes, 2015; Sarache-Castro et al., 2015). Furthermore, worldwide agreements are being reached for the reduction of greenhouse gas emissions, in order to control global warming. Environmental management systems, such as ISO 14001, as well as initiatives including ecolabels, zero-emission, and zero-waste operations (Stindt, 2017) are becoming more common in the business world each day.

Nowadays, "*the improvement of environmental performance of organizations and awareness on natural resources protection has been consolidating as key differentiating factors in world markets*" (Leguízamo-Díaz and Moreno-Mantilla, 2014). Together with stakeholders' pressure (León et al., 2016), more strict governments and market regulations (Domingo and Aguado, 2015), and more environmentally concern consumers, companies are being driven towards implementing environmental performance monitoring systems in their day to day operations (Maceno et al., 2018), including manufacturing activities.

Given the complexity associated with carrying out multi-dimensional performance assessments (i.e. economic, environmental, and social), most research has tended to approach sustainability performance from an environmental point of view (Burritt and Schaltegger, 2014; Longoni et al., 2014). A review of literature from the past 20 years on the topic of sustainable performance measurement in the field of sustainable supply chain management was conducted by Beske-Janssen et al. (2015). The results show a clear trend towards addressing environmental (141 of 149 papers) and economic (130 papers) performance. In contrast, only 49 papers addressed social performance up to 2014, and only seven of those were published prior to 2010.

Evaluation of environmental performance at industry level focus mainly on the identification of the most significant environmental impacts (Maceno et al., 2018) derived from manufacturing related (internal sources), and supply chain related (external sources) activities. Maceno et al. (2018) list available methods form environmental performance evaluation including Material Flow Cost Accounting (MFCA), Life Cycle Impact Assessment (LCIA) and Ecological Footprint (EF). These analytic methods aim mainly at monetizing environmental impacts, so they can be easily compared in terms of cash flow (or penalties), however they have weakness related to single-resource measurements, extensive databases requirements, time consuming measurement and analysis, and difficult interpretation among others (Herva et al., 2011).

There are also environmental management systems and reporting standards (or sustainability standards including environmental performance) such as GRI, MSCI and ISO14001, which nevertheless, are biased by not being specifically designed for measuring outcomes of industrial and manufacturing operations (Maceno et al., 2018) and are often difficult to employ as decision-making tools (Campos et al., 2015; Shahbazi et al., 2018) due to their qualitative or binary (present/not present) nature (Sutherland et al., 2016).

Issues have been also identified with other EP assessment methods proposed, such as Overall Environmental Equipment Effectiveness (OEEE) (Domingo and Aguado, 2015), and Net Present Sustainable Value (NPSV) (Liesen et al., 2013). Ang and Van Passel (2010) and Kuosmanen and Kuosmanen (2009), point to the problem of sustainable value approach being based on the value assigned to a particular resource. Therefore, if companies use different resources, their comparative value allocations can become biased.

A different approach to environmental monetizing and analytical methods is commonly used in OM literature, and especially in empirical research. It is based on KPIs (Shahbazi et al., 2018), for different categories of environmental impacts, including non-financial indicators, and, while not being universally applicable, it should reflect the specifies of the industry sector, be easy to interpret, to benchmark, and to calculate (Dočekalová and Kocmanová, 2016). "*Indicators quantify information by aggregating different and multiple data (necessary to obtain reliable information); thus, they can be used to illustrate and communicate complex phenomena in a simpler way, including trends and progresses over a certain period of time*" (Herva et al., 2011). Table 5 presents different categories for environmental KPIs commonly employed in manufacturing and industrial companies.

It has to be noticed that many environmental and social indicators, are affected by long-term decisions (Khodeir and Othman, 2016; WBCSD, 2010). Therefore, when dealing with public policy, long-term investments, or even some industrial projects, it is also important to consider time trends and longitudinal data, as cause-effect relationships among the measured variables can be mediated by context variables and time-lag between implementation and performance gains (Bortolotti, Danese, et al., 2015; Slaper and Hall, 2011).

Table 5. Environmental KPIs employed in manufacturing operations

Category	Description	Sources
Energy efficiency	Measures energy consumption along the value chain, but also accounts from renewable and nonrenewable energy sources	[1,2,3,4,5,6,7,8]
Material consumption	Measures raw material consumption, accounting for the use of recycled materials and by-products	[1,2,3,4,5,6,7,9]
Transportation	Includes environmental impacts generated during transportation of the product and raw materials, mainly in terms of fuel consumption and carbon emissions	[2,6,8]
Water usage	Accounts for both water usage in production processes, as well as eutrophication due to residuals	[1,2,3,5,6,7]
Waste generation	Both waste generation and waste disposal indicators are considered. Generated quantities of hazardous waste, recyclable waste, and landfill waste have different weights in measurement	[1,2,3,5,6,7,8,9]
Emissions	Gas and particulate emissions to air are also considered environmental impacts. Of especial attention are greenhouse gas, SO_2, and NO_x emissions	[2,3,4,5,6,7,8]
Legal compliance	Although legal requirements often differ from country to country, violations to environmental regulations and costs of fines and penalties are among the most closely followed indicators in manufacturing companies	[1,2,6,7]
[1] Campos et al., 2015; [2] Dočekalová and Kocmanová, 2016; [3] Helleno et al., 2017; [4] Herva et al., 2011; [5] Khodeir and Othman, 2016; [6] León et al., 2016; [7] Maceno et al., 2018; [8] Sarache-Castro et al., 2015; [9] Shahbazi et al., 2018		

1.5.3. Social performance

Social performance of companies has been closely related to their Corporate Social Responsibility (CSR). The concept has been addressed in manufacturing industry as far as 1899. Andrew Carnegie (in his book "The Gospel of Wealth") called upon some principles of what later became known as social responsibility. It mainly state that wealthiest own to the people the obligation to use their money for purposes that society consider legitimate (Sadeghi et al., 2016). Since the 1930's there has been calls for companies to be aware of its impacts in society (Carroll, 1979), but only until the 70's concerns about industries giving serious consideration to social outcomes begin to arise.

Several definitions have appeared since the 70's for social responsibility and in general for social outcomes of organizations activities. Table 6 summarizes the most relevant of them according to the time period. As evidenced by those definitions, the social responsibility concept has evolved in the past half century. From a merely "internal" perspective (i.e. the company can do his business as long as it doesn't break the law), to an "external" perspective by the end of the nineties, where a stakeholder approach begins to prevail, meaning that the company should not only focus on its "internal" affairs, but also has to consider its impact on third party actors like community and society (Siebert et al., 2016).

Table 6. Evolution of social responsibility concept

Social Responsibility Definition	Sources
Maximization of profits in a legal boundary without deception or frauds	Friedman (1970)
Bringing corporate behavior to a level congruent with prevailing social norms, values and expectations	Sethi (1975)
Obligations from corporations to society (beyond stockholders) beyond those prescribed by laws and union contracts	Jacobs et al. (2016); Jones (1980)
The duty of a corporation to protect the interests of the society, to contribute to improve life-quality of the workforce, their families, and society in general	Watts and Holme (1999)
Activities performed by an organization beyond the interest of the firm and law requirements	McWilliams and Siegel (2001)
Economic, legal, moral, ethical, and humanitarian expectations that stakeholders and society in general have of any organization at a given time	Carroll and Buchholtz (2003); Castka and Balzarova (2008); Danko et al. (2008)
Social performance becomes part of the value of products and services of a company; it will be transformed into a competitive advantage, increased profits and economic success	Dočekalová (2013)
Not just to satisfy the shareholders expectations but also to take into account all types of the firm's stakeholders	Von Hauff and Wilderer (2008); López et al. (2007); Sadeghi et al. (2016)
Provide equitable opportunities, encourage diversity, ensure quality of life and democratic processes	Zhang et al. (2017)

Own elaboration, based on: (Sadeghi et al., 2016)

This interaction (social impacts) based perspective between the company and its stakeholders is well described by Hutchins and Sutherland (2008): *"The company provides its employees with wages, and the employees, in turn, provide the company with labor, skill, and/or expertise. The company may also positively affect its employees (and their families) by providing healthcare, childcare, and education. There may also be opportunities for each of the stakeholders to have a role in guiding the values of the company; likewise, the company may help to shape the values of its stakeholders. In addition, the community and larger society may establish laws and regulations that must be met by the company. The company may contribute taxes, infrastructure, or philanthropic gifts to these outside stakeholders. Owners (or shareholders) invest financial capital in the company and the company may return some funds in the form of profits (or dividends)"*.

Social performance measurement has multiple objectives. Organizations can use it for internal purposes (for example to assess the work climate and the motivation of its employees), and for external purposes, like compliance with law requirements, or to advertise his commitment to the community (Jonkutė and Staniškis, 2016). Regardless of the reasons driving companies to measure their social impacts, it is also evident that they will expect some direct or indirect retribution for their efforts in the social front.

Consequently, an important number of authors (Chen et al., 2015; Hasan et al., 2016; Jacobs et al., 2016; Maletič et al., 2016; Rais and Goedegebuure, 2009; Sadeghi et al., 2016) have focused their efforts on presenting metrics and SP assessment methods, as part of works correlating it to the company financial or operational performance. Works in this area usually consist of empirical studies based on statistical correlation of several indicators used for SP with more established ones for financial and operational performance (ROI, sales, costs, revenues, productivity, etc.). Results present divergent conclusions, which however lean towards a positive effect of SP on the firm financial performance as shown by the three reviews presented in Table 7.

Table 7. Effects of social performance on company financial performance

Author	Reviewed Studies	Positive Relation	No Relation Inconclusive	Negative Relation
Orlitzky et al. (2003)	52	29%	69%	2%
Margolis and Walsh (2003)	127	50%	30%	20%
Roman et al. (1999)	52	63%	27%	10%
Griffin and Mahon (1997)	51	55%	14%	31%

Positive effects of social initiatives are generally related to increased productivity and efficiency due to motivation of the workforce (Jacobs et al., 2016; Rais and Goedegebuure, 2009), as well as sales and marketing benefits derived from the company's good reputation (Hasan et al., 2016; Orlitzky et al., 2003; Rais and Goedegebuure, 2009).

On the other hand, most negative impacts tend to be associated with the cost involved in maintaining social initiatives, and the risk connected to not getting the appropriate return or the long-term needed to perceive it (Maletič et al., 2016; Sadeghi et al., 2016). Also, when markets drop, companies struggle with economic survival and even a superior SP might not help, so it tends to be seen just as an additional cost (Chen et al., 2015; Jacobs et al., 2016) therefore, putting some social programs amongst the firsts to get funding cuts.

Nevertheless, as Dočekalová (2013) states, the efforts from organizations to achieve high levels of SP represent expenditures in the short-term, but in the long-term are potentially decisive for the company overall performance and sustainability. The same short-term expense and long-term return on investment has been observed in some environmental practices (Younis et al., 2016), making the social pillar of TBL not the exception to the long-term commitment required in sustainability-related practices.

1.6. Lean Manufacturing Effects on Performance

Lean manufacturing effects on performance range from positive to negative depending on different factors (Chavez et al., 2015). Positive effects have been often found on priorities like cost, quality and delivery (i.e. at operational level), especially when applied practices are interrelated (Hines et al., 2004; Negrão et al., 2017). At a strategic level (customer and value dimensions), LM can also provide positive results but it often requires that it is integrated with other approaches that don't contradict its core principles (Hines et al., 2004).

In recent years, it has been noticed that performance has to be addressed from a multi-dimensional perspective that includes environmental (Avella and Vázquez-Bustelo, 2010) and social outcomes (Elkington, 2013; Gong et al., 2018). LM is no exception to this, and interest is growing around how it links with sustainability (Cherrafi et al., 2016; Martínez-Jurado and Moyano-Fuentes, 2014), and more important, how it affects performance under a TBL approach (Bergenwall et al., 2012; Sajan et al., 2017). In spite of this, most scientific literature to date relies on the LM – operational performance approach, with LM – environmental performance growing in recent years, and LM – social performance still being the less studied relationship as shown in Figure 10.

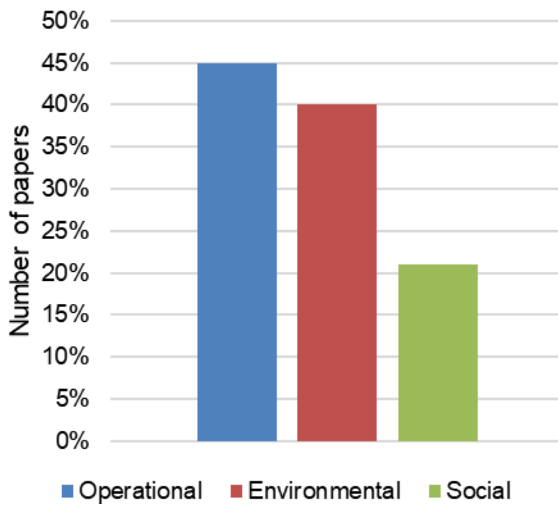

Figure 10. Outcomes measured in papers linking LM with sustainability

The next sections provide a comprehensive review of scientific literature that has addressed the LM–sustainability link, and the findings relating each pillar of performance under the TBL approach.

1.6.1. Lean Manufacturing and Operational Performance

Although some studies, such as those of Chavez et al. (2015) and Büyüközkan et al. (2015) account for operational and financial (or economic) performance as separate dimensions, under a TBL approach, financial or economic outcomes are considered to be related to the OP of a company (Slaper and Hall, 2011). As expected, the LM – OP relationship was the first to be studied in investigations dating back to the eighties. However, prior to Shah and Ward (2003) only the effects of single practices or lean principles were studied, and not LM as a package of interdependent practices that together comprise a LM strategy or philosophy.

Generally, empirical evidence supports the notion that LM implementation contributes in some degree to the enhancement of OP in several scenarios (Chavez et al., 2015; Marodin et al., 2019; Negrão et al., 2017). A successful implementation of synergistic LM practices, can account for an OP increase of up to 23% (Shah and Ward, 2003) when measuring shop floor dimensions like quality, lead time, unit cost and flexibility. Büyüközkan et al. (2015) found that OP measures tend to be positively affected up to 16% if a company reaches a 100% effective use of LM. Performance can even increase up to 20% when financial variables are considered in the performance measure. However, it can also drop to just 13% with the average level of LM implementation found on companies.

While most authors agree that LM practices are interrelated (Bortolotti et al., 2013; Čiarnienė and Vienažindienė, 2014; Shah and Ward, 2003) and their successful implementation depends on achieving some degree of balance between them, some sets of practices appear more often as the main drivers of OP gains. For instance, Belekoukias et al. (2014) found that quality is mostly affected by JIT practices, claiming that as JIT reduces the inventory levels, quality problems are more likely to be exposed and require immediate attention. In this study, JIT also had the highest impact of all LM practices on speed as well as dependability (dimensions related to on-time deliveries), and a significant positive effect on cost and flexibility. This positive JIT – OP relationship is backed by several other studies (Bortolotti, Danese, et al., 2015; Dal Pont et al., 2008; Ketokivi and Schroeder, 2004; Rahman et al., 2010; Shah and Ward, 2003; Zhao et al., 2014). There is also an identifiable pattern linking TQM implementation with an improvement in OP.

In spite of the evidence pointing to the positive effect of LM implementation on OP, there are some contributions which support the contrary, or which point towards other attenuating elements of that relationship (Bergenwall et al., 2012; Čiarnienė and Vienažindienė, 2014; Espejo Alarcón and Moyano Fuentes, 2007; Negrão et al., 2017; Pham et al., 2011). Those findings can be explained from the contingency perspective, meaning that every company needs an individual approach for its manufacturing strategy perspective. Also, some authors claim that the LM-performance link is of such complexity that it is difficult to account for all the variables mediating on it (Chavez et al., 2015).

Other explanations provided to support a negative LM – OP relationship, claim that some organizations fail to see LM as a continuous process, which could explain good results when it is a novelty, but it later falls in rank against other projects or priorities (Čiarnienė and Vienažindienė, 2014). Also, traditional LM practices are good at driving efficiency and lowering costs (waste minimization); however not all of them can be considered “fitness” practices to maintain sustained growth in changing environments. Along the same lines, Pham and Thomas (2011) assert that “*the success of Lean in companies often mirrors the classic change curve. Improvements in productivity after an intervention are soon followed by a steady decline to baseline, and sometimes even below baseline levels*”.

This happens as people return to previous ways of working, or the focus is shifted to other priorities. Čiarnienė and Vienažindienė (2014) claim that only about 10% of companies achieve a successful implementation of LM practices. Also, empirical studies reveal a high rate of abandonment of LM implementation in the first three years (Resta et al., 2017). A trend emerges from scientific literature, pointing to three basic factors determinant of the successful improvement of OP (or its detriment) through LM implementation:

- **Human factors:** Čiarnienė and Vienažindienė (2014) propose two types of barriers that lay the groundwork for limited success of LM implementation. The first ones are people-related; some issues such as attitude, resistance to change, lack of knowledge about LM and poor communication were identified (Manotas Duque and Rivera Cadavid, 2007; Ruben et al., 2018). The second are organizational barriers, for example culture, lack of resources for implementation, a weak alignment between improvement programs and the defined strategy, scarce data collection and performance measures, the tendency to return to the old ways of working, and scarce management commitment (Gobinath et al., 2015). While (Alhuraish et al., 2017) do not make a differentiation between people-related and organizational barriers, they do account for most of them in their “critical success factors” for LM. This is complemented by evidence of unionized plants being less prone to implement human-related practices such as standardized methods or cross functional training (Bergenwall et al., 2012; Shah and Ward, 2003).

Both barriers are strongly related to human behavior, whether they reflect on individual or organizational conduct. This is reinforced by Taggart and Kienhöfer (2013) findings which identified a “snowball effect” when some LM practices are forced into the workforce without previously dealing with human resource issues. These authors point out that pushing JIT and TQM onto workers untrained in LM, that are not conscious enough of how changes might benefit them in the long term, will end up jeopardizing safety and shifting the employees’ focus away from quality. Human factors were also identified in some case studies as the cause of lack of success in LM implementation (Resta et al., 2016).

- **Context factors:** contingency theories state that since all organizations are different, there isn’t a manufacturing strategy that can be applied universally (Netland, 2016). The same idea applies to LM and its practices (Hines et al., 2004), as evidence suggests that many underperforming or unsuccessful cases are related to context factors (Dal Pont et al., 2008; Espejo Alarcón and Moyano Fuentes, 2007; Rahman et al., 2010; Shah and Ward, 2003; Womack et al., 1990). In first place, LM principles originated in Japan (Womack et al., 1990), so clearly, cultural differences between Japanese companies and those around the world, may prevent all LM practices or principles to be equally applicable (Nordin and Belal, 2017) or, minimally, assimilated in other countries (Losonci et al., 2017; Negrão et al., 2017).

The influence of context factors has been documented since Shah and Ward (2003) stated that “*organizational context, i.e. plant size, unionization and plant age, matters with regard to implementation of lean practices*”. They found that, for example, larger plants were more disposed to implement most of the LM practices, with Negrão et al. (2017) also supporting the same conclusion. This fact was later supported by Rahman et al. (2010) who found that JIT has more impact on large enterprises, in contrast to other lean principles like waste minimization, which has more influence on small and medium-size enterprises’ OP.

More recent findings also point to LM being able to positively impact OP only in environments (productive and market) with a low level of technological turbulence (i.e. when technology involved in the manufacturing process remains relatively similar in the mid-term) (Chavez et al., 2015). This could be explained by the fact that LM relies heavily on standardized tasks and training (Bortolotti et al., 2013). When manufacturing technology gradually evolves from the same base, people and methods adapt quickly to those changes and are even prone to create a continuous improvement effect around technological developments. However, if technological breakthroughs are significantly different from previous technology employed, the previous methods and training might become immediately obsolete, so the learning curve has to start over again from the beginning. For this reason, one of the TPS (considered as a precursor of LM) principles is “*use only reliable, thoroughly tested technology that serves your people and process*” (Liker, 2004).

- **Sequence factors:** using the analogy of cultivating crops, the terrain has to be prepared before planting the LM seed in order for it to grow properly, develop strong roots, and produce the expected fruits in the medium and long-term. Organizational culture has been known to play a major role in this process (as the fertile ground), with some companies struggling with non-effective LM practices implementation as a result of a hostile organizational environment (Negrão et al., 2017; Ruben et al., 2018). Čiarnienė and Vienažindienė (2014) have found that the extent of the matter is such that an average company can take at minimum five years to fully implement a LM strategy.

Culture aside, the reviewed literature has revealed that it is more likely to achieve positive effects on OP when practices are implemented in a given sequence, rather as concurrently, as people struggle to cope with a large amount of changes, resources are often limited, and some practices support others (Alefari et al., 2017; Longoni et al., 2013). Practices related to the HRM bundle have been found to provide a good base structure to prepare the organization for the subsequent implementation of other practices (Dal Pont et al., 2008; Taggart and Kienhöfer, 2013) and are recommended to be introduced early. Belekoukias et al. (2014) have also found that VSM (Value Stream Mapping) is necessary as one of the first steps when implementing LM, as it points out to the processes that are more likely producing the biggest "*mudas*" (waste). However, companies must be aware that an incorrect or inaccurate VSM may lead to resources being allocated to the wrong priorities.

In a similar approach, Bortolotti et al. (2015) proposed a "sand-cone" model, where some lean bundles of practices are described as "fitness" bundles, thus providing the support needed for successful implementation of other practices and their subsequent improvements in OP. The proposed fitness base practices are JIT and TQM. As the bases from these practices grow, the organizational structure around LM not only becomes more robust in order to support other goal-oriented practices, but also becomes more capable of dealing with context variations that might affect quality, delivery, flexibility or cost.

1.6.2. Lean Manufacturing and Environmental Performance

While studies linking LM and OP are, in most cases, based on survey studies and statistical analysis, the reviewed literature on LM and EP rely mostly on case studies and frameworks (Domingo and Aguado, 2015; Galeazzo et al., 2014; Miller et al., 2010; Thanki et al., 2016; Torielli et al., 2011; Verrier et al., 2016; Vinodh, Ben Ruben, et al., 2016). This may be explained in part by the difficulty in finding appropriate EP metrics which are comparable, in different organizational contexts, in the way that quality, service, cost and delivery apply in a general sense to the manufacturing industry (Domingo and Aguado, 2015). The use of case studies has been common in manufacturing strategy research for many years. They are valuable as proof of concepts in certain scenarios, however they pose difficulties related to the generalization of the results (Bergenwall et al., 2012; Ketokivi and Schroeder, 2004).

One well-covered topic in recent LM literature explores the Lean-Green relationship, which in some cases, is closely related to EP. From this perspective, Garza-Reyes (2015) offers an important benchmark by reviewing the literature on Lean-Green from 1997 to 2014. His findings evidence some inconsistencies and contrasting results, with some pointing to reciprocal interdependencies between Lean and Green practices, and complementary effects among them, while others found that both practices differ in their essence, and so lead to different impacts on performance. Resta et al. (2016) emphasizes that, to avoid these contradictory results, LM has to be analyzed as a complete philosophy, rather than the EP impacts of some specific practices. A more recent literature review on the topic by Ben Ruben et al. (2018) arrived to similar conclusions. However, they make an important contribution identifying critical success factors (CSFs) and critical failure factors (CFFs) for LM with environmental focus. Most CFFs are related to technology, financing, and organizational policies. On the other hand, most CSFs are linked to training, and management and staff commitment.

This is also supported by Galeazzo et al. (2014) and Resta et al. (2017) conclusions that the empirical evidence available of LM effect on EP ranges from positive to negative results. Bergenwall et al. (2012) state that "…*the findings are mixed. Rothenberg et al. (2001) suggest that there may be tradeoffs involved between lean production and environmental performance and other research suggests that lean production and environmental performance are complementary*". Garza-Reyes (2015) concludes that part of the problem resides on the fact that "*there is a shortage of lean and green research focused, particularly, on developing measurement methods or models for specific processes and industries*", and that "*the lack of clear and consistent conclusions from these studies may suggest that the research done until now to try to establish the effect of lean-green practices on different aspects of organizational performance is still limited and inconclusive*".

An interesting trend emerges in related literature, which points to the EP gains achieved when LM is implemented being side effects or unintended results that won't necessarily replicate in all LM implementations (Corbett and Klassen, 2006). This claim is supported by five relevant contributions: a) Torielli et al.'s (2011) findings which imply that lean practices alone won't necessarily produce environmental benefits; b) Bandehnezhad et al.'s (2012) and Martínez León and Calvo-Amodio (2017) conclusion that there are negative environmental impacts of some JIT associated practices due to more frequent changeovers and the increase of delivery frequencies; c) Resta et al.'s (2016) "green spillovers", which mean that LM effects can lead to waste reduction and less energy and resources use; and d) Piercy and Rich (2015) acknowledgement of past research showing that "*environmental benefits have been seen as a by-product of lean operational improvement (Florida, 1996), what Corbett and Klassen (2006) term 'the law of unexpected side benefits'*".

In spite of this, there are also research results which point to a more direct, positive LM – EP relationship, and that even that relationship can have a positive influence on OP (Garza-Reyes et al., 2018; Monge et al., 2013; Prasad et al., 2016; Sobral et al., 2013; Thanki et al., 2016). Vinodh et al. (2011) propose that the LM waste minimization approach, should consider environmental waste (unnecessary or excessive usage of resources as well as substances released to air, water, or land that could harm human health or environment) to be the ninth waste (the eight being unused human potential, and the other seven the classical manufacturing wastes listed in Table 8), and therefore should be systematically reduced. They found that pull systems, associated with JIT, can result in less work in process product damage, 5S and cellular manufacturing can lead to less energy consumption (Bandehnezhad et al., 2012), and TPM can attend spills and leakages immediately, thus preventing contamination.

A possible explanation for the results of LM – EP ranging from negative, to unexpected, to positive, is derived from other studies in the literature. Evidence suggests that, while the traditional LM approach is not directly oriented towards improving environmental performance, it can be complemented with Green Manufacturing (GM) practices that build upon existing capabilities derived from LM principles (waste minimization, continuous improvement, and workforce training and empowerment, for example). Nevertheless, lean practices are not necessarily green practices. Verrier et al. (2016) propose an interesting parallel between the seven green *mudas* and the traditional seven LM *mudas*, and how they interact with each other as illustrated in Table 8.

Table 8. Lean and Green Mudas

<table>
<tr><th>Lean Mudas</th><th>Green Mudas</th><th>Interactions</th></tr>
<tr><td>Overproduction</td><td>Excessive power usage</td><td rowspan="4">Excessive power usage can be a result of almost all lean mudas, affected by overproduction, quality defects, excess inventory, inappropriate processing and transportation.</td></tr>
<tr><td>Defects</td><td>Greenhouse gases</td></tr>
<tr><td>Unnecessary movement</td><td>Eutrophication</td></tr>
<tr><td>Unnecessary inventory</td><td>Pollution</td></tr>
<tr><td>Inappropriate processing</td><td>Excessive resource usage</td><td rowspan="3">Excessive resource usage can be affected by defects, overproduction, excess inventory and waiting.</td></tr>
<tr><td>Inappropriate transportation</td><td>Excessive water usage</td></tr>
<tr><td>Waiting</td><td>Poor health and safety</td></tr>
</table>

Own elaboration, based on: (Dües et al., 2013; Miller et al., 2010; Nujoom et al., 2017; Verrier et al., 2016; Vinodh et al., 2011)

As evidenced in Table 8, while some of the green *mudas* and lean *mudas* are related to common sources, and can have similar consequences, they are by nature different kinds of waste (Dües et al., 2013), which however, can be overcome by similar waste minimization approaches. Given the different natures of LM and GM practices, their effect on EP can be also diverse. It is most likely that LM practices alone will fail to provide a significant positive improvement on EP; however, when both practices are implemented concurrently, their effects can boost not only EP, but also OP, more than if they are implemented separately (Galeazzo et al., 2014; Miller et al., 2010). This is also complemented by Jabbour et al. (2013) study, which states that "*the ability of the operations/manufacturing area to support environmental management tends to be greater when the company adopts lean manufacturing practices*", meaning that changes in organizational culture achieved through LM implementation are fertile ground for practices focused on the environment, as they share similar principles (Miller et al., 2010; Verrier et al., 2016).

1.6.3. Lean Manufacturing and Social Performance

Social performance (SP) is the least studied sustainability outcome in LM literature, and in fact, in all operations management literature (Besiou and Van Wassenhove, 2015; Cherrafi et al., 2016; Corbett and Klassen, 2006; Longoni et al., 2014; Resta et al., 2017). This could be explained mainly by two factors. First, many companies consider social issues as non-related to their core-business (Clarkson, 1995; Rais and Goedegebuure, 2009). Second, industries from developing countries, often focus mainly on achieving economic growth, leaving environmental and social performance aside (Hettige et al., 1996; Hutchins and Sutherland, 2008).

Social outcomes pose several challenges for research related to manufacturing and production strategies, since they are characterized by a fair grade of complexity due to conflicting goals from the different stakeholders (mainly organizations and communities). This creates uncertainty, divergence, and the need for trade-offs between short-term losses and long-term benefits (Besiou and Van Wassenhove, 2015).

In spite of scarce research on the matter, increasing pressure for companies to address all pillars of TBL is raising concerns about the impact of LM (and other manufacturing strategies) on society (Besiou and Van Wassenhove, 2015; Resta et al., 2016), both the group of people directly related to the organization (i.e. the workforce), and the community indirectly affected by it. This situation leads to imminent trade-offs between social and environmental performance, and profits.

The question that remains implicit is whether it is possible to achieve an optimal behavior that balances both internal operational and economic results with societal outcomes. The answers are limited from the beginning given that there is little consensus about which is the appropriate or desirable level of social responsibility that a company should achieve (Besiou and Van Wassenhove, 2015). Social metrics are either uncommon or non-comparable (Slaper and Hall, 2011), making it difficult to judge SP. However, (Pagell and Shevchenko, 2014) claim that SP is an issue that research is able to overcome as it is directly related to people's wellbeing, and measures already exist (although separately) in the form of worker's safety, long-term health, and even psychological safety.

One of few studies that directly focuses on considering LM effects on aspects that can be considered part of SP was carried out by Longoni et al. (2013). They performed a multi case study to find out how LM practices implementation impact aspects related to workers' health and safety. Their findings show that LM can do both harm and good, depending on how practices are implemented and interrelated, a conclusion shared by Resta et al. (2016). For example, the adoption of JIT requires HRM practices to develop the skills and desired level of worker involvement prior to asking for lower lead times and less waste. Otherwise, it has harmful consequences in operational and safety performance. It's the same case for TQM, as the technical system (the tools and practices involved, like SPC) has to deal with the social system (the workers) in order to succeed.

Longoni et al. (2013) findings are complemented both in their positive and negative implications. Verrier et al. (2016) consider poor health and safety as a muda (waste), and therefore expect that a company with a strong LM philosophy should be eager to minimize these risks. On the other hand, the pursuit of standardization through LM without the proper level of employee empowerment can end in routine operation (Resta et al., 2017; Sajan et al., 2017), which is often associated with a lack of improvement, slippage back to old ways of working, laxity, rule breakage, defiance, and even sabotage (Ketokivi and Schroeder, 2004).

One of the most comprehensive research on the LM-SP relationship was performed by Distelhorst et al. (2017). They used data from more than 300 apparel factories located in developing countries, to test the effects of LM implementation on SP from two different conceptual approaches. First, that lean implementation should encourage companies to retain their "lean workforce", resulting in better terms of employment. Second, that lean management capabilities should lower the costs of social initiatives, and in general of complying with social standards.

Their results support that there is some degree of positive influence of LM in SP, but some noticeable caveats remain. On one hand, they proved that LM is associated with up to 15% improvement in labor standards compliance (Distelhorst et al., 2017), however, as must labor standards change from one country to another, a high degree of heterogeneity was found on the results, with India, Malaysia, Thailand and Vietnam presenting positive results, while in Sri Lanka, China, and other evaluated countries, the effect of LM on SP was not significant. On the other hand, improvements were found to be mostly related to wage and work hours compliance, since companies were willing to offer improved conditions to retain the training effort put into the "lean workforce", however, no effect was detected on health, safety, and environmental standards (Distelhorst et al., 2017), probably because they require structural changes and investments.

Another important implication of LM effect in SP, is related to the amount of changes that a company implementing lean faces. Particularly, researchers have found that attention has to be paid to fears arising in the workforce regrading job stability (Resta et al., 2017; Sajan et al., 2017), since the elimination of “non-value added” activities and the standardization of tasks can be perceived as a precursor of “lean layoffs” (Manotas Duque and Rivera Cadavid, 2007). Resta et al. (2016) found that, in all cases, some initial opposition was present from workers dealing LM implementation, but positive results were usually achieved in the long term. Nevertheless, current studies still suffer from numerous limitations related to the appropriate measures and indexes, as well as the small samples considered (Longoni et al., 2013).

1.6.4. Lean Manufacturing and Sustainable Performance

Many of the papers asserting relationships between LM and sustainability, do not account for all TBL pillars, and instead consider sustainability to be a form of accounting for environmental impacts along with OP. Verrier et al. (2016) paper refers to the TBL perspective when dealing with sustainability. However, in practice it only addresses OP and EP issues, as is the case in other investigations which link LM and sustainability in their titles (Ishak et al., 2017; Miller et al., 2010; Nujoom et al., 2017; Vinodh et al., 2011). Martínez León and Calvo-Amodio (2017) framework addresses economic, environmental and social perspectives, but the papers used as references are restricted by the inclusion of the words “environmental” or “green” in all their search strings. Finally, the sustainability component of the OEEE (Overall Environmental Equipment Effectiveness) proposed by Domingo and Aguado (2015) only represents an environmental component, as it is calculated in terms of achieved gains on environmental impact reduction.

Due to the complexity of the variables and interactions involved in assessing SSTP, and the subjectivity of most non-economic measures (Pagell and Shevchenko, 2014), most literature available in the Lean Manufacturing – sustainable performance relationship consist of case studies (Bergenwall et al., 2012; Helleno et al., 2017; Piercy and Rich, 2015; Resta et al., 2016, 2017; Silva et al., 2013; Vinodh, Ben Ruben, et al., 2016), or frameworks (Abualfaraa et al., 2017; Pagell and Shevchenko, 2014; Sonntag, 2000). Of selected works, only Thomas et al. (2016), Sajan et al. (2017), Burawat (2019), Chavez et al. (2020) and Varela et al. (2019) have used an empirical research approach based on surveys, to test different LM-SSTP relationships. Thomas et al. (2016) identified the business profiles of manufacturing companies that lead to increased resiliency and sustainability. Their results provide four different business scenarios according to sales and costs patterns, the former being affected by turbulent markets, and the latter influenced by manufacturing strategy, including LM implementation.

The first business profile proposed by Thomas et al. (2016) is marked by decreasing sales and increasing operational costs. In the second profile, sales grow over time, but costs grow at a higher rate, thus making both profile 1 and 2 unsustainable in the long-term. The third profile has companies with decreasing operational costs (as a result of LM and other similar initiatives), but also with decreasing sales due to aging product lines. While the third profile by itself is also unsustainable over time, it gives the opportunity to the company to implement “fitness” practices based on innovation and new markets to increase sales (Pham and Thomas, 2011) and therefore, achieve long-term sustainability.

Companies belonging to the fourth business profile (represented in Figure 11), are sustainable and resilient organizations (Thomas et al., 2016), and show an extensive and embedded use of LM, but only in addition to other strategies such as supply chain integration, technology integration, agility and reconfigurability in their operations, as well as sophisticated, innovative and diverse product lines, and a multi-client portfolio for their sales (Pham and Thomas, 2011).

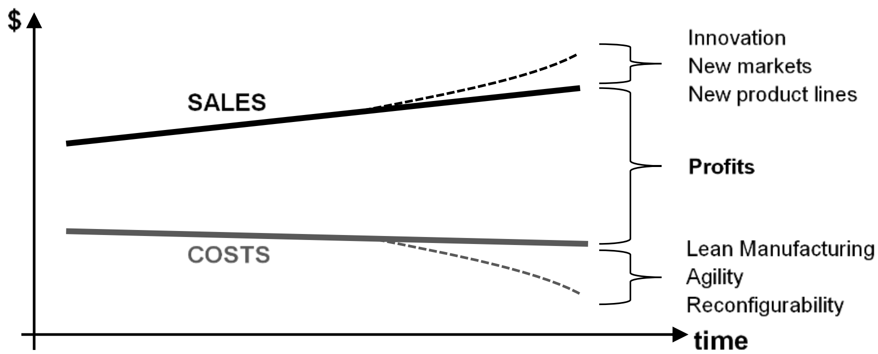

Figure 11. Business scenario for sustainability. *Adapted from: (Eldenburg and Wolcott, 2011; Pham and Thomas, 2011; Thomas et al., 2016)*

In fact, an interesting quote from Thomas et al. (2016) states that "*production managers often cited the issue that the application of Lean, Six Sigma and other process improvement programs were often run as separate change management programs and as such, the programs did not integrate effectively with the production management work being undertaken in the company*". This was found to be particularly the case with companies in business profiles 1 and 2 (the less sustainable ones), as they employed LM as a one-time strategy, which was insufficient to provide a significant SSTP.

The results of Bergenwall et al. (2012), one of the most comprehensive LM – SSTP investigation from a TBL perspective to date, also show mixed outcomes, with concern rising around benefits being achievable only in the short-term. Although their work is limited, as it represents only the case of two North American automotive companies, notable findings include the harmful environmental effects derived from the mismatch between pull and push systems in different links of the value chain, which cause overproduction and excessive inventories and therefore, increased resource consumption, land use and emissions.

There is also the concern of increased pollution due to JIT practices requiring more frequent transport, supported by the claim that "*the adoption of TPS (Toyota Production System) by many Japanese firms in the 1980s actually worsened the air quality in Tokyo*" (Bergenwall et al., 2012), which is also supported by Fahimnia et al. (2015) and Martínez León and Calvo-Amodio (2017). Finally, they also pointed to negative SP outcomes since American unions are found to be traditionally reluctant to cross-training (one common practice of HRM) in order to protect job security, hence workers often feel threatened by the implementation of such LM practices.

Piercy and Rich (2015) and Vinodh et al. (2016) seem fonder of a positive relationship between LM and SSTP, although both of them are mostly focused on environmental outcomes. Value stream mapping (VSM), regarded as a starting point for LM implementation, can be extended to "map" environmental impacts through product lifecycle, improving EP (Vinodh, Ben Ruben, et al., 2016). Worker training, empowerment, standardized work, and visual management tend to deliver higher levels of worker safety (Piercy and Rich, 2015), while supplier development (associated with both JIT and TQM) can improve EP as synchronization with suppliers leads to less overproduction and transportation. Similar to lean and green practices, Piercy and Rich's (2015) framework differentiates lean practices from sustainability practices, although they propose a model for integrating the two (Figure 12).

Operational level (workplace) sustainability accounts for waste reduction and improved work conditions, supply chain sustainability includes local sourcing and supplier audits, and community sustainability addresses engagement with schools, neighbors and charity sponsorship. Both lean and sustainability practices can be complementary, but need to be implemented using different approaches. As LM can start from operational level, it can rely either on bottom-up or mid-level-up implementation, while sustainability has to be adopted from the organizational strategy, making it more suitable for the top-down approach.

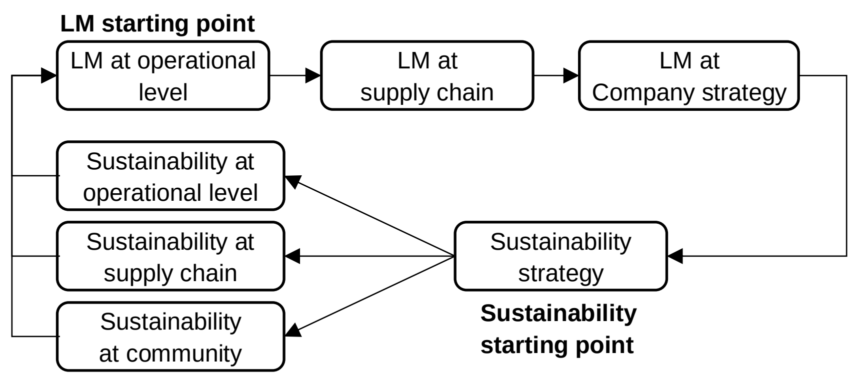

Figure 12. Model for LM and sustainable operations integration. *Adapted from Piercy and Rich (2015)*

It's important to consider that in Piercy and Rich's (2015) investigation, being based on case studies, goals, outcomes or metrics used to assess sustainability effects, especially regarding SP were different in each company. The authors acknowledge "*while the change cases here are focused on the positive achievements of each company it should be noted that transformation was not necessarily always smooth*" (Piercy and Rich, 2015).

Most recently, Resta et al. (2017) performed a multi case study on manufacturing companies from different sectors, exploring how the introduction of LM practices contribute to sustainability goals. Their findings support the breadth of positive LM-OP relationship, but further claim that the adoption of HRM practices help to build a "lean culture" in the organization, therefore, positively impacting SP. On the other side, some of the cases presented a negative LM-EP relationship. This seem to be particularly the case in companies where there wasn't a clearly defined sustainability (or environmental) strategy.

Resta et al.'s (2017) results, partially diverge with those of Sajan et al. (2017), since the latter found significant positive effects of LM on all three TBL dimensions. Sajan et al.'s (2017) structural equation model was developed from data of 252 Indian small and medium enterprises. Interestingly, the LM-EP relationship resulted stronger and most significant than LM-OP and LM-SP, but the authors did not provide possible explanations for this result. Therefore, while being an important contribution to the lean and sustainability literature, especially regarding SP, Sajan et al.'s (2017) results are limited by sampling being done in a particular state in India, with multisector companies.

The complexity and multi-dimensional nature of the LM-sustainability interaction has been established on several occasions, with the identified effects of LM on the TBL pillars ranging from positive to negative in reviewed works, as presented in Table 9. An important caveat of LM effects shown in Table 9, is that some performance dimensions have been found to be affected either positively or negatively. Also, certain authors have found both positive and negative outcomes. An explanation may be provided by number of context variables that can affect LM effectiveness, the negative interaction between some lean practices and specific performance dimensions, and also, to a failure of viewing LM as a cohesive philosophy, instead of a set of separately implemented tools.

Table 9. LM effects on operational, environmental, and social performance

	Positive effects (improve in)	**Negative effects (detriment in)**
Operational performance	Cycle time ([1], [2], [7], [10], [24], [30]) Scraps and reworks ([1], [2], [18], [20]) First pass yield ([1], [2]) Manufacturing cost ([1], [2], [5], [6], [7]; [9], [10], [22], [24], [31]) Lead time ([1], [2], [5], [6], [8], [18], [24]) Product quality ([5], [6], [7], [9], [10], [18], [22], [25]) Quantity flexibility ([2], [5], [6], [9], [22]) Product mix flexibility ([2], [5], [7]) Inventory reduction ([18], [21], [29])	Financial performance (in high technological turbulence [3], [8], [15], [21], [31]) Long-term improvement ([8], [21], [26]) Misallocation of resources ([4], [7]) Administrative cost ([4]) Manufacturing cost (incorrect VSM [7]) Product quality (incorrect VSM [7]) Flexibility (incorrect VSM [7]) Lead Time ([18]) Quality ([9], [10], [18])
Environmental performance	Resource consumption ([11], [14], [16], [20], [24], [25], [27], [28], [29], [30], [31]) Pollution control ([11], [14], [20], [24], [25], [27], [28]) Energy efficiency ([12], [13], [14], [16], [20], [24], [25], [28], [29], [30]) Recycling ([13], [16]) Environmental awareness ([16], [17], [25], [28]) Carbon footprint ([17])	Waste disposal ([11], [28]) Pollution ([11], [21], [27], [28]) Energy consumption ([21], [28]) Trade-offs with operational performance ([23]) VOC emissions ([28])
Social performance	Multifunctional teams ([4], [29], [30]) Health and safety ([9], [14], [25], [28], [29], [30]) Continuous improvement ([9]) Employee satisfaction ([17], [18], [25], [28], [29], [30])	Employee reluctance to cross-training ([21]) Employee mistrust ([4], [26], [29]) Safety ([9], [21]) Work climate ([9], [19], [28]) Routine operation ([10], [21], [29]) Traffic ([11], [21], [28], [29]) Trade-offs with operational performance ([23])
[1] Shah and Ward (2003); [2] Dal Pont et al. (2009); [3] Chavez et al. (2015); [4] Čiarnienė and Vienažindienė (2014); [5] Bortolotti et al. (2015); [6] Zhao et al. (2014); [7] Belekoukias et al. (2014); [8] Pham and Thomas (2011); [9] Longoni et al. (2013); [10] Ketokivi and Schroeder (2004); [11] Bandehnezhad et al. (2012); [12] Torielli et al. (2011); [13] Miller et al. (2010); [14] Verrier et al. (2016); [15] Galeazzo et al. (2014); [16] Jabbour et al. (2013); [17] Monge et al. (2013); [18] Negrão et al, (2017); [19] Nordin and Belal, (2017); [20] Vinodh et al. (2011); [21] Bergenwall et al. (2012); [22] Domingo and Aguado (2015); [23] Besiou and Van Wassenhove (2015); [24] Vinodh et al. (2016); [25] Piercy and Rich (2015); [26] Thomas et al. (2016); [27] Pagell and Shevchenko (2014); [28] Resta et al. (2017); [29] Resta et al. (2016); [30] Silva et al. (2013); [31] Sonntag (2000)		

The three most recent empirical studies in the reviewed literature come from Burawat (2019), Chavez et al. (2020), and Varela et al. (2019). Interestingly, their conclusions, although drawn from research conducted in different countries, still presents contradictory results. Burawat (2019) collected data from a large sample of more than 370 Thai companies from different manufacturing sectors and used SEM to test the mediating effects of different kinds of leadership between LM and sustainability. Their findings support a positive effect of LM on sustainable performance, which, interestingly, resulted more significant in companies related with the automotive industry. A noticeable limitation from Burawat's (2019) research is that sustainable performance is considered as a single latent construct, which makes impossible to discern the effects of LM on each TBL performance dimension.

Varela et al. (2019) also applied SEM to test the effects of LM and Industry 4.0 practices on TBL performance. In contrast to previous results of Burawat (2019) and Sajan et al. (2017) they found that while Industry 4.0 has a positive effect on sustainable performance, the effects of LM were not statistically significant, which, by the authors own acknowledge, was unexpected. Their possible explanations for the results suggest that lean was not originally conceived as a holistic performance improvement paradigm. On the other hand, the results of Chavez et al. (2020), also obtained through SEM of data gathered from a sample of Chilean manufacturing companies, suggest that internal lean practices have positive effects on both environmental and social performance, but, in contrast to most available literature, have no effect on operational performance. To explain this, they argue that the selected "internal" lean practices, do not cover the entire spectrum of lean manufacturing, but instead are more focused in organizational strategic improvements than singular operational improvements.

1.7. Colombian metalworking industry

Colombian manufacturing industry development has been marked by several waves that have contributed to a non-constant grow in industrial production and sophistication that have left some sectors of manufacturing trailing the world leading industrial economies by several decades, trying to keep the pace of other developing countries in a globalized economy. The roots of Colombian manufacturing industry can be found by the end of the 19th century, when a mostly agricultural country began to develop industries around the basic needs of a developing economy as an answer to the expensive costs of importing and its long lead times. In this way, textile, construction materials, basic chemicals, and some iron industries were the first to be established (Mayor-Mora, 2002). The country's organic development aided by some socio-political milestones at the beginning of the 20th century (the coffee golden age and the economic compensation for Panama's separation) led to a rapid development of the manufacturing industry that was affected by the great depression of the thirties as a direct consequence of the United States being Colombia's main commercial ally.

The Second World War marked another development wave. As the world leading economies were focusing all their manufacturing resources on the war effort, Colombia (and several other countries not directly related to the global conflict) began to experience several shortages of imported products, especially those whose raw materials were essential for war purposes (Jaramillo-Mejia, 2001). With private capital and in some cases government aid during the war and post-war period, many manufacturing companies were established to substitute the non-available products. Metalworking was established at that point as one of the fastest growing industries in the country since steel, aluminum, copper (and other metals) were among the most rationed raw materials in the fighting countries (Jaramillo-Mejia, 2001). That in turn led to a surplus of non-war related industrial machinery that perfectly suited the Colombian market demands of products such as hand tools, construction materials, nails, screws, cooking utensils, etc.

Until the nineteen seventies, the Colombian manufacturing industry continued to grow at a steady pace, aided by protectionism, as well as favorable conditions for the establishment of multi-national companies. At that point, the manufacturing industry contributed to 23% of the country's GDP and was considered one of the main development engines in three fronts as a driver of economic development, as a modernizing and technological transformation sector, and as a productive diversification and social transformation agent (Garcia, 2002).

After the eighties, the industry turned into a period of ups and downs, with the technological revolution and globalization phenomena not being unfamiliar to the Colombian context. The end of the 20th and beginning of the 21st century was marked by the opening of the Colombian market and the rapid dismantling of government protectionism that left an ill-prepared industry open to global competition (Carranza Romero et al., 2018). That process was also joined by a gradual de-industrialization represented in a drop of its participation in the country's GDP to around 12% by the first decade of the 21st century (Maldonado, 2010; Santa Maria et al., 2013). Figure 13 also shows a deceleration in the industrial GDP rate of growth that was about 6% in the seventies, to a negative average in the nineties, and 1,2% in the present decade, which is about a third of the overall GDP growth rate for the same period. However, this recent deceleration rate of industrial production has been lower than the rest of the world (Carranza Romero et al., 2018).

The metalworking sector is not an exception to the general behavior of Colombian manufacturing industry, enduring the above-mentioned difficulties in recent years. One of the most significant problems is considered to be the access to competitive sources of raw materials (Ramirez et al., 2011), which almost always is imported in such a way that makes the industry dependent on international availability, as the domestic supply chain has little vertical integration derived from the scarce local production.

Steel and ferrous metals products account for most of the raw material processed in the metalworking industry, making its supply one of the most vulnerable links in the supply chain given that Colombian steel industry only provides about half of the country's needs (Henao and Sarache, 2015) with an average of 1,6 million tons per year of production against a 2,9 million tons of internal demand. Moreover, most of the local production goes to the construction industry as that has been one of the most dynamic sectors of the economy, making it more attractive to domestic steel producers (Salcedo et al., 2014).

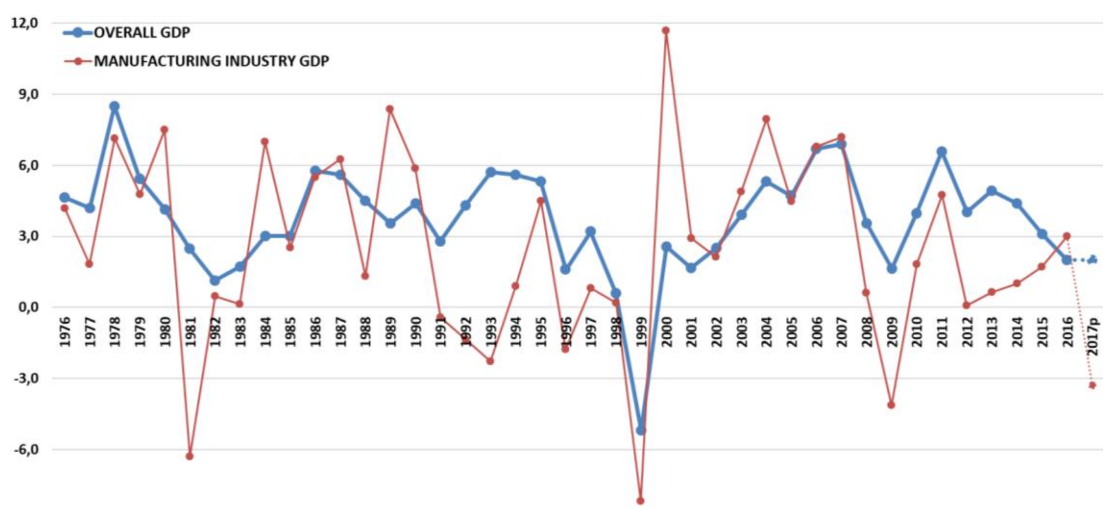

Figure 13. Overall Colombian GDP and Industrial GDP variation. *Based on data from (DANE, 2017)*

An important aspect of Colombian metalworking industry, is that it comprises mostly SMEs, which despite vast experience in their fields, lack the capacities to cover more markets and become often dependent of single clients (such as automotive assembly plants), compromising its long-term sustainability (Orozco and Aguirre, 2014). Despite the described difficulties, the metalworking industry (comprising also steel production and shipyards) remains an important link in the entire

Colombian productive chain, accounting for 13% of the entire industrial GDP. ANDI (*Asociacion Nacional de Industriales*), Colombian industrial guild, concluded that in order for the Siderurgy and Metalworking productive chain to become more competitive, it requires among other things, to support the technological development and scientific research in the sector. Furthermore, they claim that this productive chain is crucial to the country's development, as it accounts for 13,5% of the workplaces of the entire manufacturing industry, and 12% of its sales (Ramirez et al., 2011).

Gutiérrez (2010), proposed a classification of the Colombian metalworking industry into nine groups according to their main production focus (shown in Table 10). He also concluded that the sector is concentrated in six main regions: Bogotá, Sogamoso and Duitama; Cali and Yumbo; Medellin (metropolitan area); Atlantic Coast (Barranquilla, Soledad, Cartagena and Mamonal); Bucaramanga (metropolitan area); and Caldas (Manizales, Villamaria, Pereira and Dosquebradas).

Table 10. Colombian metalworking industry composition

Classification	**Main productive focus**
Group 1	Automotive industry
Group 2	Agricultural machinery and equipment
Group 3	Machine-tools
Group 4	Machinery and equipment for different sectors. Includes non-electric equipment manufacturing for activities such as food and beverage industry, construction, textile, etc.
Group 5	Industrial electric equipment
Group 6	Home appliances and diverse electrical equipment
Group 7	Different metallic products. Includes non-ferrous siderurgy, metallic furniture, cutlery, cookware, metallic ornaments, etc.
Group 8	Steel and ironworks
Group 9	Professional and scientific material

Adapted from: (Gutiérrez, 2010)

Research of LM application in Colombian metalworking industry (along with manufacturing and service industries) is scarce and show that LM implementation is still done mainly pursuing economic/operational outcomes (Arrieta et al., 2011). However, there is also evidence suggesting that some Colombian industries perceived environmental benefits from the application of some LM practices (Leguízamo-Díaz and Moreno-Mantilla, 2014; Velásquez, 2012), but it remains unclear if it is an unintentional result rather than a concrete goal when the decision to implement LM was taken. Furthermore, a recent review of different publications related to the Colombian metalworking sector performed by Figueredo Garzon et al. (2020), concluded that said sector requires a significant competitiveness improvement if it aims to continue evolving and remain sustainable in the long term, and suggest that in order to achieve that, cost reduction and quality management strategies (such as lean manufacturing) should be employed.

There is also an important consideration regarding the adaptability and cultural sensitivity of lean practices and its implementation. As most lean practices originated in Japan, they might not come as natural to Colombian (or non-Japanese) companies due to context and cultural issues (Danese et al., 2018; Nordin and Belal, 2017). Therefore, the adoption of LM requires some level of adaptation in order to render it sustainable and useful to an organization, however, there is scarce evidence that such lean adaptations have been thoroughly studied in Colombian industry, and if the core principles of LM have been retained through the process. Instead, there is evidence pointing out that most of the early lean adopters in Colombia have done as a requirement from their customers, especially those working with automotive companies (Arrieta et al., 2011; Sanchez, 2017), or trough government founded initiatives (González Gaitán et al., 2018; León et al., 2017), which leads to a more constricted lean implementation. This approach seems to be consistent with the implementation of LM on other developing countries (Rajagopalan and Solaimani, 2019; Walter and Paladini, 2019), prompting authors such as Antony et al. (2021) and Psomas (2021) to call for more country-related LM research in order to address the above mentioned issues.

From a sustainability perspective, there have been increasing pressures from different sets of stakeholders for Colombian manufacturing companies to improve their environmental and social performance. On one side, with globalization and the information era, customers are more informed about the source of the products they consume, and awareness has increased regarding the negative impacts that manufacturers could have on the environment or society. On the other hand, local legislation has become more strict concerning environmental and social protection, in part thanks to several free trade agreements signed by the Colombian government in the past decade (Bartels, 2013; Harrison et al., 2019). This has led to improved labor and environmental standards that are comparable with their counterparts (mainly USA and the European Union), and the obligation from government institutions to oversee the implementation of said standards in a reasonable period of time (Orjuela-Castro et al., 2019; Ramirez-Contreras and Faaij, 2018).

The enforced pursuit of sustainability on Colombian manufacturing companies (whether it comes coercive or as an indirect requirement of its customers or different stakeholders), has pose however a significant problem to industries as they were often been forced to improve their sustainable performance alone, while still facing the imperious need to improve their competitiveness in a challenging market (Figueredo Garzon et al., 2020). This was also reinforced by a recent research of Hernandez et al. (2020) who evidenced a lack of scientific publications around the subject and concluded that "*it is necessary to improve the efforts to construct and spread scientific knowledge around the research and implementation of practices that contribute to achieve a sustainable industry*". Public policies have been recently developed to support the implementation of sustainability practices in manufacturing industries, and the pursuit of sustainable development goals, which are mainly considered in the "National Policy for Sustainable Production and Consumption" (Ministerio de Ambiente Vivienda y Desarrollo Territorial, 2010), which however, is outdated by more than ten years, and therefore, it is unlikely to be aligned with the most recent global challenges regarding sustainable development.

It is also important to notice other factors related to the both the dependent and independent variables of this research that supports the choice of the objective population. First, a large part of Colombian metalworking industries take part on the automotive supply-chain (Preciado Hernández et al., 2018), and therefore, were amongst the early adopters of lean methodologies and practices in the country through knowledge transfer from the main actors of the automotive industry in the nineties and early two thousand, Colmotores (General Motors Colombian assembly plant) and Sofasa (Renault Colombian assembly plant), with their MGC (*Modelo de Gestion para la Competitividad* - Competitiveness Management Model) program (Forero, 2009; Sanchez, 2017). This process was also spearheaded by the other main assembly plants present in the country, such as Mazda and Hino Motors (a Toyota owned company), and common export customers in nearby countries like Ford (Venezuela) and Chevrolet (Ecuador), who implemented their own supplier development programs.

Second, while the manufacturing industry provide employment for approximately 22% of the world working-age population (Sutherland et al., 2016), it is also accountable for a significant amount of world-wide pollution generation and other environmental and social impacts (Dočekalová and Kocmanová, 2016). Colombian companies are not an exemption from this phenomena, and given the relevance of the metalworking industries in the country manufacturing chain, this sector faces remarkable challenges in face of long-term sustainability and competitivity (Figueredo Garzon et al., 2020; Sanabria, 2014). Such challenges are acknowledge by both companies, academics, and government institutions, with the country Environment, Housing and Territory development ministry being commissioned by the government to develop policies focused on sustainable production and consumption in line with the different worldwide agreements on the matter, such as, the Kyoto Protocol, COP21 agreement, and the UN SDG's (Castro et al., 2020).

Such policies are in great need of being completed, but more important, implemented by Colombian metalworking companies, with Sanabria (2014) claiming that the Colombian metalworking industry needs to "*optimize resources with the aim of applying a sustainable model in the organizations*" and that in this industry sector "*it is possible to evidence a lack of resource optimization and commitment to environment and society*". In spite of such claims, a recent study from Morelos-Gómez et al. (2021) found that interesting developments have occurred in the metalworking sector of Cartagena, with companies using process innovation to achieve sustainability goals.

In this context, the Colombian metalworking industry represents a highly interesting sample of the development and implementation of lean manufacturing practices and how they have been adopted and adapted to meet lean goals and principles in a developing country environment with remarkable differences from the original environment where those were developed. It also presents a good opportunity for measuring the impacts in the different dimensions of sustainability at different levels, providing a good opportunity to understand the studied phenomenon (i.e., the effect of lean manufacturing on sustainable performance) and test the proposed hypotheses.

Finally, with the metalworking sector being an important link of the country productive chain, the obtained results from the selected sample and conclusions from the present research, could be used to develop much-needed public policies regarding sustainable production, provide companies and practitioners with better understanding to achieve successful lean manufacturing implementations (that reflect in performance improvements), and contribute to the wealth of knowledge in said fields worldwide. It is even possible to achieve some level of extrapolation and generalization to other Colombian manufacturing sectors, given the high relevance and representativeness of the metalworking industry.

1.8. Lean manufacturing in SMEs

Colombian metalworking sector is largely composed by small and medium enterprises (SMEs) (Figueredo Garzon et al., 2020; Morelos-Gómez et al., 2021; Preciado Hernández et al., 2018). Therefore, the discussion surrounding the different relationships between LM and SMEs becomes relevant to the theoretical backgrounds of this research. In spite of lean principles and goals being somehow universal, regardless of the company size (Burawat, 2019), research has found multiple evidences that the level of adoption of LM can be different in small and large companies (Shah and Ward, 2003), and that many lean CSF, such as lean implementation time, rate of success (or desertion), management commitment, and more importantly, the sustainability of the perceived benefits can also result different in SMEs (Grigg et al., 2020; Marodin et al., 2019).

A large number of articles regarding LM on SMEs has been published in recent years (Belhadi et al., 2018), making it a topic of growing interest among academics and practitioners. In general, results of studies reported in literature seem to revolve around two main arguments. The first states that, since lean implementation requires a vast commitment of resources, large companies are more prone to be successful as they have both the capital, human resource, and technological means to run a sustained lean program (Tortorella et al., 2017). In contrast, their small counterparts are more likely to be focused on short-term survival (Sajan et al., 2017) and lacking a long-term vision and commitment required by LM (Belhadi et al., 2018; Zhou, 2016).

The second trend might seem contrasting at first glance. It poses that, since cultural change is one of the main barriers for LM implementation (Alhuraish et al., 2017; Zhou, 2016), small companies might embrace lean with a more flexible "open-mind" approach, contrary to the more rigid definition of processes that can be expected from a large company (Antony et al., 2021; Belhadi et al., 2018). In this context, it is likely that the changes in the traditional way of doing things required by lean can be more expedite in SMEs (Shah and Ward, 2003). Also, the perceived benefits of lean in the short time could be more appealing to small companies on which "every penny adds" (Dey et al., 2020; Zhou, 2016), whereas large companies are likely to have been applying some form of continuous improvement program (even if they don't have a lean program) that leaves less room for radical improvements.

There are results published in literature that provide support to both trends. For example, Walter and Paladini (2019) concluded that larger companies are more likely to implement LM, a notion shared by Tortorella et al. (2017). They said that one of the main reasons could be attributed to the dominant position of the large company through the supply chain. This gives them the possibility to coerce their suppliers (and in some cases even their customers) to adopt lean practices such as JIT deliveries. This dominant position of large companies, forcing the adaptation of their upstream and downstream supply chain in accordance to their manufacturing strategy was evidenced by Womack et al. (1990) more than 30 years ago widely spread along the automotive supply chain. Shah and Ward (2003) also concluded that large companies were more likely to implement 20 out of their 22 considered lean practices. Interestingly, their results also revealed that large companies are less likely to translate lean implementation into improved operational performance, which supports the second trend in which lean benefits are more easily achieved in small companies.

Also in line with the second trend, Alhuraish et al. (2017) concluded that SMEs can achieve successful implementations of LM as long as they do it on a sequential way. They argue that, as long as SMEs comply with the CSF for LM, there should be no significant difference in their implementation when compared to large companies. This vision is shared with other authors, including Burawat (2019), Dey et al. (2020), Sajan et al. (2017) and Thanki et al. (2016), with all of them agreeing that, given the right conditions, LM can be successfully applied in any company regardless of its size. Interestingly, although Zhou (2016) also agrees that LM can be implemented in SMEs and that the CSF are shared between small and large company, they suggest that the relative importance of CSFs can differ according to company size. In small, low lean level companies, the main challenges for LM implementation revolve around the required cultural changes, the lack of resources (mainly time), and the scarce know-how of lean practices, whilst in large companies the main challenges are the tendency to return to the old ways of working, the required cultural changes, and employee resistance to change.

Another interest finding in literature is that, while large companies usually can afford to run self-founded corporate-level lean programs (Belhadi et al., 2018; Tortorella et al., 2017), SMEs often depend on external consultants and externally (usually government) founded programs to implement LM (Grigg et al., 2020; Losonci et al., 2017; Yadav et al., 2020). These findings are consequent with what seems to have been the entry path for LM to most Colombian SMEs. As mentioned in the previous section, the main Colombian automotive assembly plants founded a lean deployment program for their suppliers (Forero, 2009; Sanchez, 2017). Also, a large number of SMEs have profited in recent years from "Fábricas de Productividad"[1] program, which is founded by the Colombian government through the Industry and Commerce ministry, and many others have also participated in the "Pro-motion"[2] project, which was founded by UNIDO (United Nations Industrial Development Organization), KOICA (Korea International Cooperation Agency), and the Colombian government.

In this context, in the studied object (the Colombian metalworking industry) mainly composed by SMEs, a widespread level of LM implementation could be expected. While Colombian SMEs face several challenges described in the previous section, the help of government, international, and customer founded programs, has allowed many of them to implement at least some lean practices in their processes. This result a critical factor to the empirical phase of the present research, as it is important that, in order to test cause-effect relationships between the studied variables (LM implementation and sustainable performance), different levels of LM implementation (ranging from low to high) are preferred to be obtained across the collected sample.

1.9. Knowledge Gap Definition

Literature and backgrounds review of LM presented in the preceding sections, suggest a knowledge gap around the lack of understanding on how lean manufacturing practices affect the sustainable performance of metalworking industries from a triple bottom line approach. Said knowledge gap, as suggested by the state-of-the-art review, can also extend to other kinds of manufacturing industries, as well as those located in other countries around the globe. As it was widely exposed, effects of LM implementation on operational performance are well documented and show a trend of positive relationship mediated by some contingencies related mainly to cultural, strategic, and timing issues.

A breadth of literature also explores LM and environmental relationships, but mainly from a lean-green practices interrelation, rather than a direct effect of LM on environmental performance of companies, which still leaves questions and gaps in this regard. Finally, the LM and social performance relationship has been studied to a lesser extent, but recent literature often calls for more research on the social outcomes derived from LM implementation, and the many gaps surrounding this promising topic. Figure 14 summarize the mainstreams identified in this theoretical framework that led to the declared knowledge gap.

[1] https://www.colombiaproductiva.com/fabricasdeproductividad
[2] https://www.pro-motion.com.co/

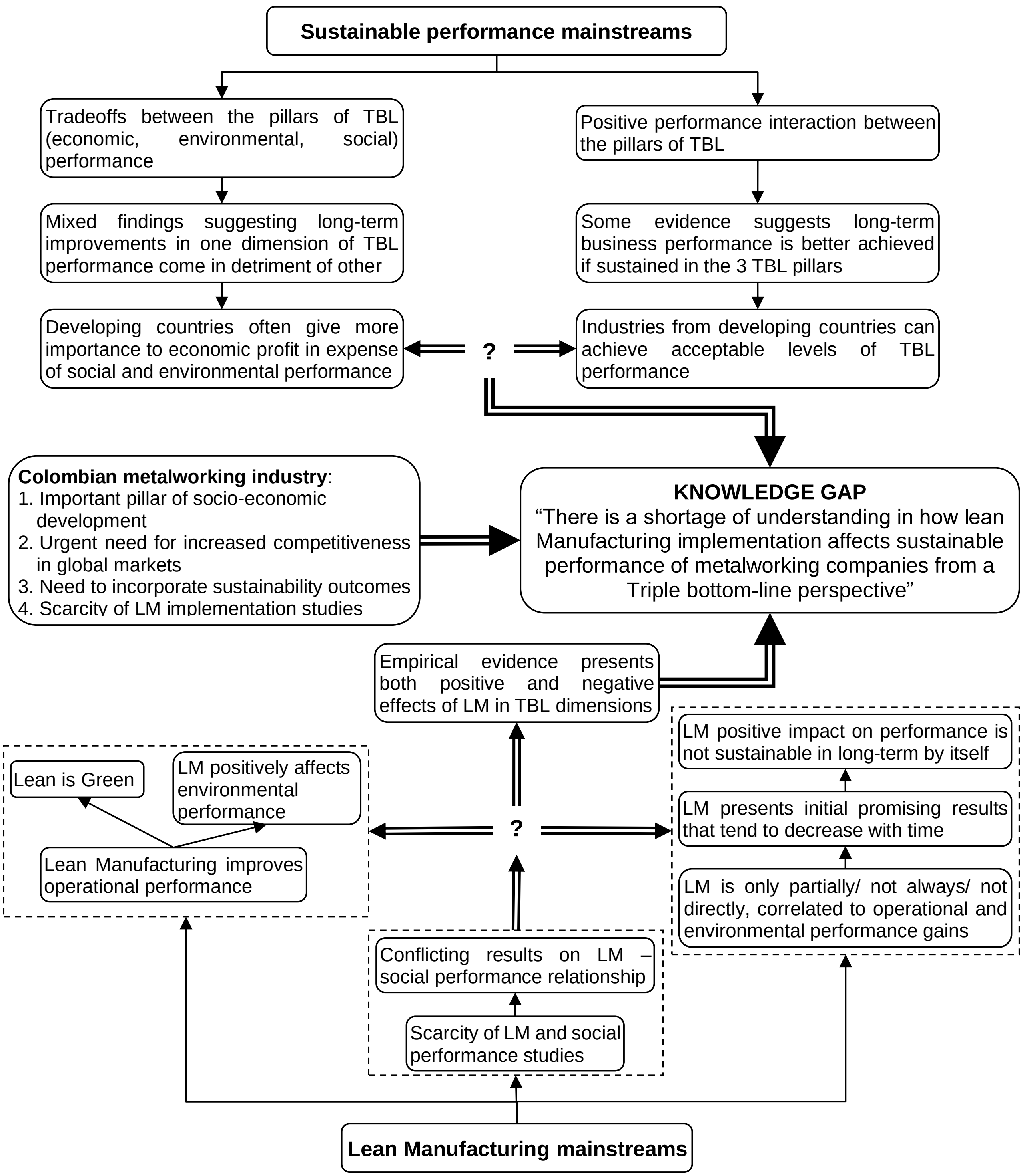

Figure 14. Knowledge gap definition

Research approaching LM links with sustainability from a TBL perspective remain very scarce, with few studies presenting frameworks and reviews, and even fewer presenting empirical evidence, while leaving several gaps around the LM sustainability interaction and constant calls for more investigations. This makes the field of study a promising ground for research, as it is important to gain adequate clarity in the short and mid-time, if LM is enough as a paradigm to achieve proper levels of sustainability in the manufacturing industry, or if it must be complemented by other practices and philosophies. The proposed research gap was clearly evidenced by Danese et al. (2018) SLR regarding the state of the art of lean manufacturing research, calling for future research on sustainability lean outcomes, arguing that it should have both academic and managerial relevance in "*promoting the adoption of lean in all processes, focusing on social aspects and considering safety/risk and environmental issues to achieve considerable advantages also in the long term*".

1.10. Partial Conclusions

Lean manufacturing has established as one of the most influential paradigms in manufacturing and management (Hines et al., 2004). However, there are still several questions surrounding how LM performs when dealing with multi-dimensional performance goals, as those required by sustainability and TBL approaches. The inconsistent results in several LM implementations (ranging from positive to negative), also raise concern around the long-term sustainability of the performance gains derived from its practices and tools.

A positive interaction between LM and OP can be achieved in most cases as long as human, context and sequence factors are taken into account. To achieve significant improvements in EP, it is most likely that LM practices need to be complemented by specifically developed green or environmental practices, which nevertheless, could be aided in their success by previous LM implementation. Regarding SP, there is the need for more research aimed at understanding the way that LM affects organizational SP. Also, it is necessary to define and adopt more widely accepted indexes and dimensions to measure social performance from both internal and external perspectives.

In addition, commonly accepted and widespread measurement scales for sustainability need to be developed according to the current and future needs of the stakeholders involved, in order to better understand how companies are performing and therefore develop more effective paths to improve sustainable performance, since the LM – sustainability integration remains one of the major challenges in current operations management research.

Concerning the most commonly employed research methods, the complexity of the variables and phenomena involved in current LM vs performance research requires more comprehensive research approaches, such as action research, longitudinal data analysis, multi-case studies, or ethnographic studies, among other methods, suited to showing better paths to sustainability, without leaving aside empirical and survey methods suited to finding general relationships between practices and performance.

To conclude, investigations linking LM and SSTP are still scarce, and results range from positive to negative interactions and outcomes. This makes the field of study a promising ground for research, as it is important to gain adequate clarity in the short and mid-term of whether LM is enough as a paradigm to achieve proper levels of sustainability in the manufacturing industry, or if it must be complemented by other practices and philosophies. However, current LM research still falls short of properly identifying, proving, and more importantly addressing issues regarding its impact on long-term sustainability, while pressure from stakeholders increases every day for the development of sufficiently effective, applicable, and scalable manufacturing strategies and practices, which positively reinforce all three TBL pillars, and discard or replace those which do not.

CHAPTER 2. METHODOLOGY

2.1. Introduction

This chapter presents the step-by-step description of the methodological approach followed by the present investigation, which follows an empirical research paradigm. Empirical and experimental research has been a source of new knowledge development for mankind for many centuries, with more structured and complex methods for each approach arising in the twentieth century thanks to advances in electronics, sensors, computing, and software, which allow scientists to gather and process large quantities of data.

Empirical research can be defined as the collection of data related to a specific phenomenon through the use of sense and instruments previously prepared to that aim, and the subsequent analysis of the gathered data (Robergs, 2010). In this kind of research, the main goal is to obtain objective and, to some degree, generalizable results (Steenhuis and de Bruijn, 2006), which however, in order to contribute to scientific knowledge must be analyzed in view of theoretical backgrounds (Marczyk et al., 2010) to confirm or reject existing paradigms or derive new ones.

Empirical research has been widely employed in OM, as it provides a picture of a given reality with the possibility to generalize to a broader spectrum, which enhances the possibility of building connection between research results and practical implications and applications (Steenhuis and de Bruijn, 2006). However, in this context, empirical research is constrained by the amount of variables and environmental conditions that affect the results and are not controlled by the researcher (Marczyk et al., 2010). This makes the selection and planning of a correct methodological approach an important task, to maximize the degree of applicability of the results, ensure the integrity of the obtained conclusions and minimize the uncertainty, bias, and other phenomenon's that might affect the results (Marczyk et al., 2010).

The methodological approach presented in this chapter, and employed by the present research, follows an hypothetic-deductive approach which has been applied to similar empirical research by numerous well-known authors and thesis in engineering and management (Bortolotti, Danese, et al., 2015; Chavez et al., 2015; Furlan et al., 2011; Machuca et al., 2011; Velásquez, 2012), as it provides consistent and reliable results from empirically collected data. The general structure is in accordance to the De Groot empiric cycle (Steenhuis and de Bruijn, 2006) shown in Figure 15, which is considered as the general base of new knowledge development from empirical research.

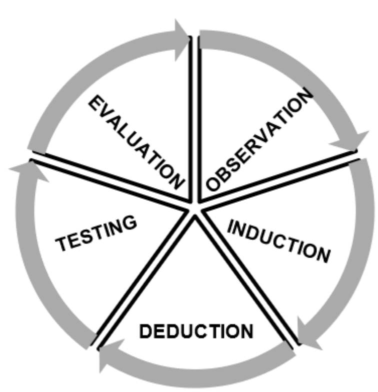

Figure 15. De Groot empirical cycle. *Adapted from: (Steenhuis and de Bruijn, 2006)*

It is also important to mention that the proposed research can be described as causational as it evaluates the cause-effect interaction between two main variables: lean manufacturing and sustainable performance. Therefore, this chapter presents the research approach and perspectives, followed by the general design and steps. It then proposes the hypothesis, operationalization of variables, and the design of the data collection instruments. Finally, it presents the field-work design, including the testing and validation of instruments, and the statistical processing methods.

2.2. Research Paradigm

In a general sense, research can be defined as a systematic process used to establish objective facts in order to generate knowledge. On the other hand, philosophy deals with different matters regarding the perception of reality and existence (Sefotho, 2015), therefore, it deals itself with the existence and perception of knowledge and how it can be approached. In a more specific way, ontology (a branch of philosophy) deals directly with questions related to the existence of a given reality, and its meaning to people (Dillon, 2016). Knowledge can be conceived as the understanding and assumptions around a given reality (Bauer, 2017), therefore, the very existence of knowledge has to be approached from an ontological position.

Epistemology (a different branch of philosophy), deals instead with how knowledge is created (Chacón Vargas, 2017), and the different methods and approaches in which it can be obtained, and finally, communicated (Scotland, 2012). It can be said in this context, that conducting research without assuming defined ontological and epistemological positions, could lead to results that are questionable in their very existence, in their ability to reflect the studied reality (or object), and in their scientific validity and reproducibility. Or as Sefotho (2015) puts it, “philosophy is like a roadmap for research without which ones’ investigation lacks illuminated direction”.

Assuming and declaring an specific “research paradigm” becomes necessary in any research in order to align ontological and epistemological positions with the research methodology (Bauer, 2017; Scotland, 2012). In a broader sense, the research paradigm can be interpreted as the bases from which “the world is observed”, and therefore, a given phenomenon or object[3] is studied, which is often termed as a “worldview” (Sefotho, 2015). The philosophical worldview therefore influences the way in which research is practiced, results are interpreted, and conclusions are drawn (Creswell, 2014).

“*Worldviews are cognitive, perceptual, and affective maps that people continuously use to make sense of the social landscape and to find their ways to whatever goals they seek. They are developed throughout a person’s lifetime through socialization and social interaction. They are encompassing and pervasive in adherence and influence. Yet, they are usually unconsciously and uncritically taken for granted as the way things are. While they rarely alter in any significant way, worldviews can change slowly over time. A worldview can hold discrepancies and inconsistencies between beliefs and values within the worldview. Hence, worldviews often contain incongruencies.*” (Hart, 2010).

[3] In the context of social sciences, the studied object can refer to people, groups or organizations. Therefore, the “world” in which those objects are encompassed can be understood from own experiences, or those of others (Sefotho, 2015). Although this research is conceived within the field of engineering, it deals with operations management practices which can be approached in the context of social sciences as they study people and organizations interactions in their social settings (Caplan, 2015).

2.2.1. Methodological approach

Scientific research has been marked by two dominant paradigms: one of quantitative research (sometimes referred as the "scientific method"), and one qualitative research (often called "social research" or "non-experimental research") (Marczyk et al., 2010). In spite of marked divisions between both approaches, they cannot be seen as completely opposite, since no research can be approached from an exclusively quantitative or exclusively qualitative perspective. Instead, research tend to be "more qualitative" or "more quantitative" depending on several factors (like methods, topics, data collection instruments, etc.). This perspective has originated the "mixed method approach", which sits in the middle of the other two approaches (Creswell, 2014).

Figure 16 presents the prominent methodological, ontological, and epistemological characteristics of the qualitative-quantitative research continuum, which are consequent with the positions adopted by the present research, and explained in detail in Sections 2.2.1, 2.2.2, and 2.2.3. In addition, Table 11 summarizes the main differences between ontological and epistemological assumptions regarding quantitative and qualitative approaches.

Qualitative research focus on the description of problems, experiences, behaviors and opinions (Muaz Jalil, 2013), which are subject to the researcher own interpretation and appreciation (Creswell, 2014). Data typically comes from interviews, field immersions, case studies, and focus groups, while data synthesis usually builds from particular to general subjects. Qualitative methods are idiosyncratic, which means that they build a close connection between the researcher and research object, thus being more personal and subjective (Bauer, 2017).

Table 11. Nature of reality and knowledge creation

Quantitative Paradigm	Qualitative Paradigm
Realistic ontology (objective reality)	Relativistic ontology (subjective reality)
A single reality exists and can be determined	Reality is multiple and relative to individuals, cultures, groups
Scientific description and explanation of reality	Sensuous reality
Talks about the properties of and relations of things	Talks about the multiple experiential realities and its diversity
Quality and descriptions are quantified	Narrative account of multiple properties
Determines definitive truth and denounces subjective truth by measuring it objectively via numerical translation.	Recognizes that there is no definitive truth only subjective truth.
Provides a sedimented and limited view of concerns but highly measurable and computable.	Provides an in-depth understanding of concerns that is not conceivable by means of statistically based examinations.
It provides reduced, decidedly controlled but predictive understanding of concerns. It applies deductive logic: from general to particular	It centralizes and places primary value on comprehensive and holistic understandings, and in what way actors comprehend, experience and maneuver within environments that are dynamic and collective in their groundwork and construction. It applies inductive logic: from particular to singular

Adapted from: (Hernández Sampieri et al., 2010; Vasquez, 2013)

Quantitative analysis seeks to delimit information and facts in order to precisely measure the variables involved in the observed phenomenon or object (Hernández Sampieri et al., 2010). It follows an empirical cycle in which hypotheses are derived from objective theories and then tested following experimental or quasi-experimental designs. These hypotheses regard the interaction and connection between variables that are, by definition, measured through quantitative instruments (Creswell, 2014). Retrieved data is usually statistically analyzed with aims of providing generalizations of the observed phenomenon or subjects, on a given sample, to an entire population.

Regarding the use of quantitative methods in social sciences (which include management), Bauer (2017) pose that they are "*nomothetic, i.e. treating the social world like the natural world focusing on the concepts themselves and their measurement and aiming at generalization*".

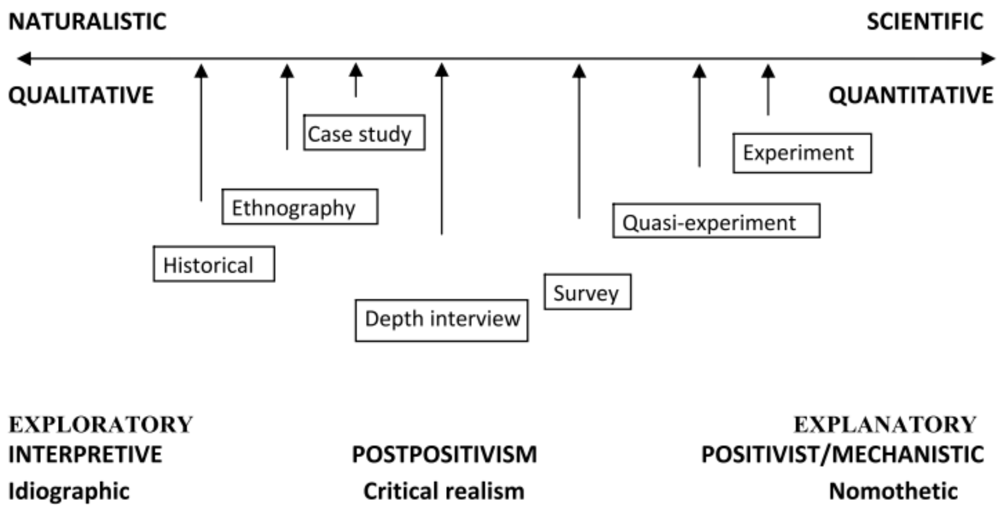

Figure 16. Characteristics of qualitative, quantitative, and mixed research. *Source: (Bisman, 2010)*

A common concern with qualitative methods regards validity, reliability and reproducibility, as they encompass a large amount of subjectivity from the researcher (Haq, 2014; Healy and Perry, 2000). On the other hand, purely quantitative methods can lead to conclusions based on statistical generalizations that not necessarily make sense in the light of existing theories or are simply product of random events[4]. Table 12 presents some known advantages and disadvantages of both approaches. Such problems, can be partially overcome with the use of mixed methods, which has increased their use in operations management research in recent years (Jasti and Kodali, 2014).

Table 12. Advantages and disadvantages of quantitative and qualitative methods

	Quantitative	**Qualitative**
Advantages	• Relatively easy to administer • Can include large number of questions • Can yield large samples • Emphasizes reliability	• Captures more depth and provide insights as to the "why" and "how" • Emphasize validity • Easier to develop
Disadvantages	• Data may not be as rich or as detailed as qualitative methods • Usually are harder to develop • May not provide sufficient information for interpretation	• Time consuming to capture and analyze • More subjective and may be difficult to summarize and compare systematically • Difficult to have large sample • Very demanding to administer

Source: (Muaz Jalil, 2013)

As Haq (2014) suggests "*The justification of mixed methods use in social research is based on the pragmatic philosophical position and explicates that social realities can be better understood by using both qualitative and quantitative data collection and analysis methods in the same research*". This implies that even from a predominantly quantitative and objective approach to data gathering and processing of the observed phenomenon, without a proper critic interpretation of the data in light of existing theories, which imply a certain degree of qualitative-subjective perspective, the new

[4]A paper from Matthews (2000) found a strong statistical correlation between human birthrates and storks populations. The author wanted to evidence the weakness of drawing light conclusions from purely statistical data, without proper analysis and criteria. This is a commonly criticized risk of quantitative methods.

knowledge generated from the research results will be less pertinent to academics and practitioners (Bisman, 2010; Healy and Perry, 2000).

This research follows a mixed method approach, which, while being more leaned to quantitative methods, still requires from important inputs derived from qualitative methods, as Figure 17 shows. The proposed methodology encompasses a sequential exploratory design (starting from the retrieval and analysis of qualitative data (steps 1, 2 and 5)), followed by a hypothetic-deductive model, as base for the derivation of hypotheses and definition of variables (steps 3 and 4), and empirical, for gathering and analyzing quantitative data (steps 6 to 8) (Chatzoglou et al., 2018; Creswell, 2014; Velásquez, 2012). Finally, the data is interpreted, and conclusions drawn in the light of both qualitative and quantitative results (step 9).

As presented, the hypothetic-deductive approach lies on a solid theoretical and conceptual framework, which allows to drawn hypothesis, select the proper variables to test them, and give explanations and draw conclusions from the gathered data (Creswell, 2014). As Marczyk et al. (2010) present it, "*prior to collecting any data at all, researchers must typically identify a topic area of interest, conduct a literature review, formulate a researchable question, articulate hypotheses, determine who or what will be studied, identify the independent and dependent variables that will be examined in the study, and choose an appropriate research methodology*".

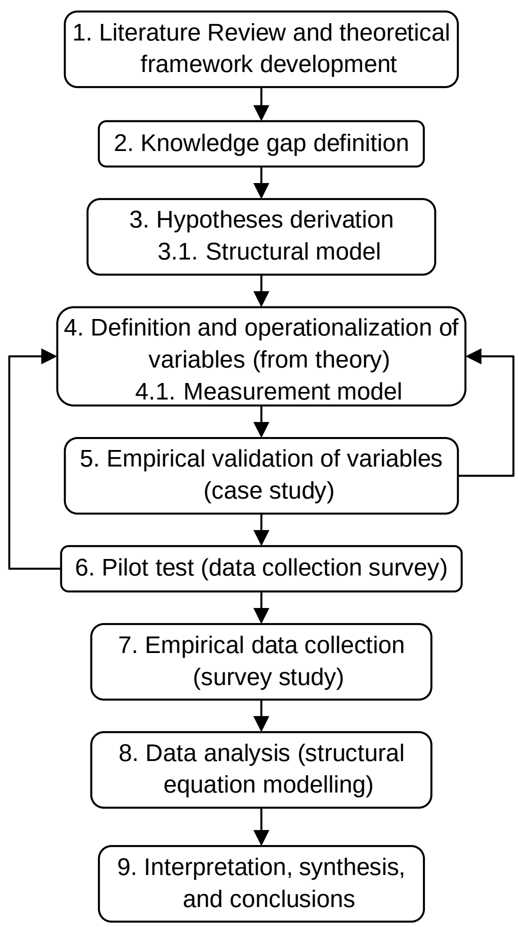

Figure 17. Methodology

Precisely from previous studies in literature, and while defining the "who will be studied", the qualitative part of the proposed mixed approach, especially the fifth step, comes relevant. Lean manufacturing has been found to be dependable on cultural context by previous research (Cardona, 2013; Fullerton et al., 2014; Henao et al., 2019; Kull et al., 2014), and there is also evidence that a gap exists between what LM philosophy and principles say, and the best way to put them into practice (Čiarnienė and Vienažindienė, 2014; Espejo Alarcón and Moyano Fuentes, 2007). In this way, the interpretations, practices and tools comprising each principle to be empirically measured through the data collection instrument should not depend only on the "state of the art", but also on how that state of the art is implemented by the best practitioners on the studied context, and consequently, the interpretation and conclusions drawn from the retrieved data should not rely exclusively on the statistical processing (Resta et al., 2017).

By that mean, a case study is proposed to narrow the gaps between theory and practice, and how LM is apprehended in the studied context (i.e. Colombian metalworking industry). The importance of a proper context immersion even in predominantly quantitative research was noted as far back as Campbell and Cook (1979) which stated "*Field experimentation should always include qualitative research to describe and illuminate the context and conditions under which research is conducted*". Moreover, Kaplan and Duchon (1988) claim that along with the purely quantitative data, an interpretation is necessary to make a research useful, and that requires an "*attempt to understand the way others construe, conceptualize, and understand events, concepts, and categories*".

Case studies become relevant when there is a lack of well supported definitions and metrics for subsequent empirical (i.e. survey) studies (Bergenwall et al., 2012; Shahbazi et al., 2018). Additionally, a properly conducted case study will contribute to establish a satisfactory level of validity and reliability of the studied construct (Nawanir et al., 2018; Nordin and Belal, 2017). In this context, the case study method allows to identify best practices from "high performing companies" (Hubbard, 2009), as well as narrow the gaps between scientific literature and the way in which companies implement lean manufacturing in their cultural and geographical context (Danese et al., 2018; Rahman et al., 2010).

The empirical-analytical part of this research (steps 3, 4 and 6 to 8), which is mostly quantitative, follows a commonly used approach in previous LM, and OM research, like those of Abdul-Rashid et al. (2017); Avella and Vázquez-Bustelo (2010); Belekoukias et al. (2014); Bortolotti, Danese, et al. (2015); Chavez et al. (2015); Garza-Reyes et al. (2018); and Sajan et al. (2017). It implies a thorough conceptualization of variables (i.e. the measurement model), and a definition of hypothetical relationships between those variables (i.e. the structural model) based on known theories (Bagozzi and Yi, 2012; Hair et al., 2009). Data is collected on a large sample through surveys, and statistically processed using purpose-built SEM software like LISREL or AMOS (Davcik, 2014).

Structural equation modelling has become one of the most employed statistical methods in LM, OM (and management in general) research (Henao et al., 2019; Khalaf Albzeirat, 2018), thanks to its ability to explain multiple complex relationship among several non-directly measurable variables known as constructs (Hildebrandt and Temme, 2006). In business, OM, and industrial applications those constructs are usually used to represent measures related to strategy, performance, SCM, HRM, LM principles, and other parameters related to the operation (Abolhassani et al., 2016; Chatzoglou et al., 2018; Rais and Goedegebuure, 2009).

The words of Davcik (2014) summarizes the versatility of SEM: "*SEM is a statistical methodology that undertakes a multivariate analysis of multi-causal relationships among different, independent phenomena grounded in reality. This technique enables the researcher to assess and interpret complex interrelated dependence relationships as well as to include the measurement error on the structural coefficients*". However, it is very important to mention that since the interaction among variables in SEM is a complex one, some researchers fail to obtain proper conclusions because of poorly structured constructs, inappropriate use of measurements or observations, dimensioning of the sample, or lack of understanding of the conceptual backgrounds of the studied problem.

2.2.2. Ontological position

Creswell (2014), refers to the term "worldviews" to describe "*a general philosophical orientation about the world and the nature of research that a researcher brings to a study*", however, he also acknowledges that research paradigms, methodologies and, epistemology and ontology, are often used to encompass the same meaning. Furthermore, Scotland (2012) suggests that research paradigms are composed by both epistemology, ontology and methodology.

Since the ontological assumptions deals with how the researcher perceives the reality of things being observed and studied (Vasquez, 2013), even before trying to draw knowledge from this reality, it's important to begin with declaring an ontological position which will guide the researcher on "what to look for" when observing a phenomenon, and how to capture it and extract knowledge from it (Bauer, 2017; Sefotho, 2015). Table 11 provides a parallel between the nature of reality between the leading quantitative and qualitative research paradigms.

As Table 11 shows, the main ontological dilemma in each research approach is the existence of a singular reality, or the multiplicity of it. It then goes on dealing if this reality (or multiple realities) can be captured, measured, and established. Ontological *realism*, aligns with the view of having a singular reality, which exists independent of the researcher, and therefore, can be objectively observed and determined without being affected by the observer (Scotland, 2012). *Realism* follows a cause-effect (or sometimes associative) approach to the existence of a given phenomenon (Bisman, 2010). In this way, as there is only a singular reality, each phenomenon has a set of causes (instead of being randomly occurring) that can be determined and measured using an appropriate research method. This approach is often called "empirical reality" (Vasquez, 2013).

In contrast to *realism*, *relativism* gives a subjective approach to the nature of reality, meaning that actual reality differs from person to person (Scotland, 2012). In this way, while conducting research, the perception of reality is influenced by the researcher, and therefore, the studied object (or phenomenon), the method, and the researcher itself, form a bundle that determines a given reality, that can be different if studied from another object-researcher-method bundle. The *relativism* approach acknowledges the fact that researchers cannot be fully objective, as reality is given by their singular perception and experience, which is often called "subjective reality" (Vasquez, 2013). This multiplicity of reality also influences the way in which knowledge is created, given that it will be constructed based on a given experience of reality by the researcher. This approach is therefore related to the *constructivism* paradigm, which implies that there is not a singular objective reality, since all realities are socially constructed (Haq, 2014), and in consequence knowledge is a subjective construction of reality.

The present doctoral research will be undertaken using a mixed approach. The predominant ontological position is one of *realism*, which goes along with a predominant quantitative research approach that will be used to gather and analyze data related to the studied phenomenon, following and empirical-analytical methodology (as presented in Section 2.2.1). This paradigm follows an ontological position of objectivity, assuming that a single reality exists about the observed phenomenon (in this case, the effects of LM implementation on Sustainable Performance of a given company), and this reality can be understood and described using quantifiable data and facts (Haq, 2014).

The main objective of the present research is to identify the effects of lean manufacturing (a given set of manufacturing practices, principles and strategies) on industrial performance from a triple bottom line perspective. This means that an assumption of the existence of a given effect (positive or negative) of LM on sustainable performance is taken as a fact, and that interaction can be identified, described and measured following a scientific approach, which relies in ontological *realism* and *objectivity* (Bauer, 2017). This paradigm is undertaken from the field of industrial engineering, favoring a quantitative approach.

In spite of the above paragraphs, it is important to understand that there is also a qualitative component in this research. While the engineering perspective covers the empirical-analytical approach and quantitative data gathering, the interpretation of results needs to be nurtured with a different perspective, closely related to management, and therefore, social sciences. This complimentary approach is what constitute a mixed method, and in consequence, pose a *critical-realism* ontological position. "*Critical realists presume that a reality exists, but that it cannot be fully or perfectly apprehended. It is recognized that perceptions have a certain degree of plasticity and that there are differences between reality and people's perceptions of reality*" (Bisman, 2010).

The reasoning behind the *critical-realism* ontology, is that while there is only one reality (i.e. as posed by *realism*), the interpretation given to that reality and the underlying cause-effects relationships is subject to a human "worldview", and therefore might differ from one individual to another (Bisman, 2010). Since lean manufacturing success has been found to be related to cultural issues (Fullerton et al., 2014; Henao et al., 2019; Kull et al., 2014) and human interactions (Bergenwall et al., 2012), and operations management deals with business, organizations and companies, which are, by definition, social constructions (Caplan, 2015), present the need to incorporate a component of qualitative analysis from a social sciences perspective.

As Bisman (2010) suggests, "*Critical realist research may be initially qualitative and inductive, enabling issues, propositions and models to be developed, clarified and modified, then followed by the hypothetic-deductive approach (most commonly used in quantitative accounting research), to unearth knowledge concerning broader mechanisms and tendencies*". It is important to notice that this ontological worldview (i.e. *critical-realism*) is situated under the umbrella of *post-positivism* epistemology (as Figure 16 shows), aligning the chosen ontological and epistemological positions of this research, as pointed out in the next section, and the methodological approach described in the previous one.

2.2.3. Epistemological position

Each field of knowledge has dominant research paradigms, which in turn, have common epistemological positions, making the choice of a given epistemology for any research, an important matter that has to render a certain degree of compatibility with previous research of the same particular field, so theoretical backgrounds follow a similar line of knowledge creation. This however, doesn't mean that all research on a given field has to be approached by the same epistemology.

In the field of operations management, Steenhuis and de Bruijn (2006) have identified three dominant epistemological approaches: *interpretivist* (*constructivism*), *design sciences* (*pragmatism*), and *positivist* & *postpositivist*.

The *interpretivist* paradigm, often combined with *constructivism* (Creswell, 2014), pose that knowledge gathered from an observed phenomenon or object is an interpretation of the researcher, therefore, there will be as many different realities as different researchers (Bisman, 2010). In this approach, the researcher and research object cannot be separated, as the meaning of any observation is influenced by each own interpretation (Steenhuis and de Bruijn, 2006). This epistemological perspective is closely related to qualitative methods such as case studies, which require an in-depth understanding of a given phenomenon, in order to capture the "story behind it", however, it will not have the same level of objectivity and generalizability of other approaches (Haq, 2014; Hernández Sampieri et al., 2010).

The *design* approach sees business research as a design science. It seeks to propose solutions to practical problems following a scientific approach, which as in *pragmatism*, are pluralistic (multiple solutions for a given problem), problem-centered, and real-world practice oriented (Creswell, 2014; Sefotho, 2015). This approach, nevertheless results problematic from a scientific point of view as generalization of a successful solution for a given problem is not necessarily valid in different contexts (van Aken, 2005). In spite of this, the reasoning behind this perspective is that OM research needs practical applications (Moshonsky et al., 2019), therefore, it's a case of "*the professional solving a practical problem and the scientist analyzing how the professional solved the problem*" (Steenhuis and de Bruijn, 2006).

The *positivist* approach is closely related to quantitative research, as it follows an objectivity-based paradigm (Steenhuis and de Bruijn, 2006). In this approach, the researcher and research object are considered independent, so any different researcher has to draw the same impartial knowledge from the observation of the same subject or phenomenon (Scotland, 2012). This "absolute truth" approach to knowledge was criticized during the 19th century (Creswell, 2014), with different scientists and philosophers underlying two major concerns: first, that the behavior and actions of humans cannot be fully described by absolute scientific theories; and second, that scientific theories cannot ever be completely proven true, in line with the principle of falsification (Creswell, 2014; Scotland, 2012).

During the 20th century, *post-positivism* emerged as an evolution to *positivism* (Sefotho, 2015), sharing similar ontological and epistemological principles, specially objectivity (Bisman, 2010), but acknowledging that no truth is absolute, and that even through the scientific method the testing (and prove or rejection) of all hypothesis will always remain tentative (Scotland, 2012). The *post-positivist* approach aims at identifying cause-effect relationships, from which laws and theories are formulated seeking generalization. Knowledge generation in this worldview is based in careful and methodic observations and measurements of objects and phenomenon's which can be undertaken in the "real world" or in controlled environments through experimentation (Hernández Sampieri et al., 2010; Scotland, 2012).

From an epistemological perspective, the present doctoral research will be approached primarily from a *post-positivist* viewpoint. This means that objectivity will be pursued through the scientific method, and it is understood that the researcher and research object are considered independent of each other. Nevertheless, the observations made by the researcher will be influenced by his backgrounds and previous experience, and even by the experience acquired during the research. Aligned with this, the preferred methodological choice is one of experimentation, data collection, and manipulation and testing of hypothesis (Creswell, 2014; Steenhuis and de Bruijn, 2006). It involves data collection, through observation at first, and then by means of surveys and testing using statistical models that allow an appropriate level of results generalization, in line with well-known and commonly accepted OM, engineering and business research paradigms (Bisman, 2010; Scotland, 2012; Steenhuis and de Bruijn, 2006).

2.3. Hypotheses system

The hypothesis system was developed around different possible correlations between the dependent and independent variables identified in the research problem and aimed to contribute to narrow the previously identified knowledge gap (Section 1.9). This research is aimed at identifying the effects of LM on sustainable performance from a TBL perspective, hence, the independent variable is a construct of different dimensions regarding Lean Manufacturing implementation, and dependent variables are constructs developed around operational, environmental and social performance measures.

The development of hypotheses is grounded on the theoretical framework presented in Chapter 1, from which it can be concluded that the LM – SSTP, and in fact, most sustainable manufacturing research, is marked by two trends: the complementary perspective and the trade-offs perspective (Henao et al., 2019; Resta et al., 2016). The first supports that there are positive interactions between all three pillars of TBL, as some authors point to a positive relationship between EP and OP; and others extend it also to SP (Lankoski, 2009; Ocampo and Estanislao-Clark, 2014; Sajan et al., 2017). From this perspective, performance in all three dimensions is cumulative, thus, if LM has been proven to deliver positive outcomes in OP, those should further lead to gains in EP, and finally SP. This cumulative approach is often known as a "sand-cone" approach.

The second perspective realizes that organizations necessarily face trade-offs between all three pillars of TBL, or at least two of them, most commonly, between economic and non-economic performance (Ciccullo et al., 2018; Figge and Hahn, 2012; Gong et al., 2018; Martínez León and Calvo-Amodio, 2017; Ocampo and Estanislao-Clark, 2014; Pagell and Shevchenko, 2014). This implies that improving in one dimension of performance will necessarily come at the expense of one or both others. The findings of Sajan et al. (2017), also support the trade-offs perspective, between economic and social dimensions, claiming that a conflict of interests has always been present on companies among those entities of sustainability.

Both approaches have been widely discussed and used in the field of operations management to describe how different manufacturing capabilities interact with each other, as presented in Figure 18.

However, this research pretends to extend said conceptual approaches to explain the interactions between sustainable performance dimensions in the presence of lean manufacturing, which, although suggested or implied in some of the reviewed literature, have never been employed, to the author's knowledge. Suggestions of both sustainability trends were identified in Ciccullo et al.'s (2018) literature review on lean supply chain and sustainability. Dealing with lean, agile, and sustainable practices, they found evidence of supporting (i.e. lean and agile practices enhance sustainable performance), synergistic (i.e. implementing all sets of practices at the same time creates an integrating interaction), and complementary (i.e. lean and agile practices are adapted to make them coherent with sustainability principles) paradigms. However, they also found evidence of competing paradigms, with lean and agile practices implementation negatively affecting environmental performance in favor of an improved operational performance.

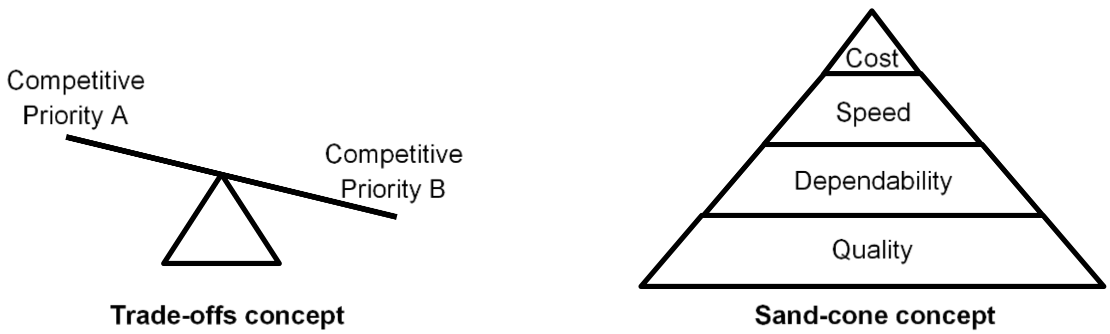

Figure 18. Trade-offs and sand-cone approaches in OM

Gong et al.'s (2018) review also found evidence of both perspectives in literature. They call "affordability theory" the argument that companies with outstanding economic performance, can afford to invest in improving their environmental and social performance. On the other hand, while specifically mentioning the "trade-offs" approach, they focus on the profitability of resources invested in environmental and social programs. Another SLR conducted by Solaimani and Sedighi (2020) in the context of lean construction also suggest that both conceptual trends can materialize while adopting lean practices. On one side, they conclude that most lean principles have "reinforcing" effects on sustainable pillars, such as TQM having positive impacts on costs (operational), safety (social) and resource usage (environmental), therefore, being in-line with the cumulative approach. However, they also point to some evident trade-offs, like "*economic cost of quality, employees' safety and circular production vis-a-vis the socio-environmental tangible and intangible benefit*".

In this way, the main hypotheses proposed for this research follow each of these two trends, presenting a theoretical background for each case and suggesting the relationship between variables (lean manufacturing and sustainable performance) that allow to test each of them (i.e. structural models). As suggestions for both theoretical models are equally present in literature, and research regarding the effects of LM in sustainable performance is still on its infancy, this research will test both the proposed approaches simultaneously regardless of if they result contradictory, complementary or independent. In this way, a more comprehensive contribution to the theoretical and practical understanding of the studied phenomenon is expected to be achieved.

2.3.1. Hypothesis 1: cumulative approach

In operations management, the "sand cone" concept to building cumulative capabilities, one on top of the other, was proposed by Ferdows and De Meyer (1990). They stated that if approached in right sequence, with the proper allocation of resources, baseline manufacturing capabilities (such as quality and dependability) allow a company to overcome trade-offs with seemingly opposite capabilities (like flexibility and cost). The concept was further expanded by Schroeder et al. (2011) adding new empirical evidence that pointed to a contingency theory regarding the capabilities sequence (i.e. there is a different appropriate sequence for each company), rather than the prescribed quality-dependability-flexibility-cost sequence originally proposed by Ferdows and De Meyer. Finally, Bortolotti et al. (2015), extended the concept to LM, suggesting (and providing empirical evidence), that the implementation of so-called “fit practices”, related to HRM, TPM, and SCM, lays the foundation for the implementation of “lean practices” (related to TQM and JIT), that in turn lead to cumulative performance gains in quality, delivery, flexibility, and cost.

This first hypothesis builds on the “sand cone” concept to provide an explanation on how LM affects sustainable performance measured from a TBL perspective. Based in evidence presented on the next paragraphs, it suggests that LM produces a positive direct effect on OP. As “wealthy” companies are expected to perform better in environmental and social aspects, OP (driven by LM) leads to EP and finally to SP, as Figure 19 suggests. The hypothesis will be proven if the indirect effects of LM leading to SP an EP through OP result stronger than the direct ones.

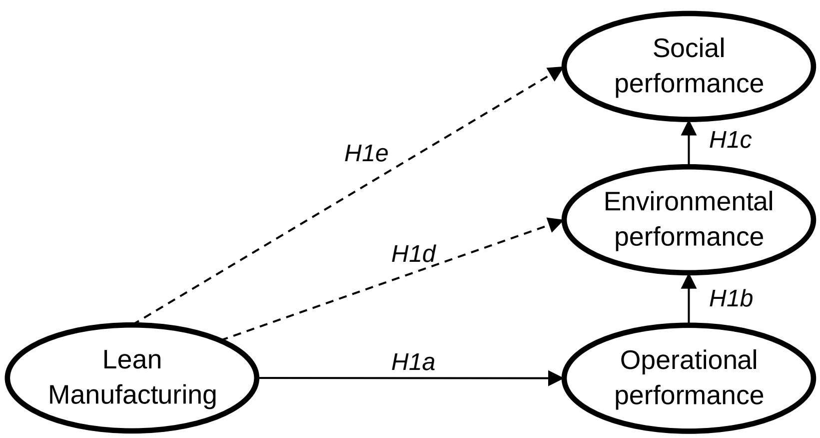

Figure 19. Hypothesis 1 structural model

From many years now, there has been strong evidence supporting that a proper implementation of lean manufacturing principles, supported by a well-selected bundle of interrelated practices and tools results in significant improvements in operational performance (Dal Pont et al., 2008; Liker, 2004; Shah and Ward, 2003; Womack et al., 1990). The positive effects of LM have also been extended to environmental outcomes in some cases (Garza-Reyes, 2015), with the lean “manufacturing waste minimization” approach providing an effective platform for environmental waste reduction (Nujoom et al., 2017; Verrier et al., 2016). However, since Florida (1996) there has been suggestions that the relationship between LM and EP is not necessarily direct, but instead, most of them come as a unintended result of operational improvement, what Resta et al. (2016) effectively call “green spillovers”. The claim that LM practices alone don’t necessarily lead to environmental benefits is also supported by Thanki et al. (2016), and therefore, it is likely that green manufacturing practices have to implemented to ensure significant environmental gains (Galeazzo et al., 2014; Henao et al., 2019).

In spite of this, companies with a strong operational performance, derived from a successful LM implementation are likely to have the foundations, principles, and more importantly, the resources to drive environmental programs that effectively improve EP (Jabbour et al., 2013; Martínez León and

Calvo-Amodio, 2017; Verrier et al., 2016). Therefore, as Figure 19 shows, a direct LM-EP effect could be expected, but EP comes mainly from an indirect effect through OP.

On top of the cumulative “sand cone” of performance lies social performance. As stated in Section 1.6.3., the effects of LM in SP remains the least studied ones (Henao et al., 2019; Resta et al., 2017). This leads to expect a lower degree of direct effect of LM in SP, or even a negative effect as previous research has also suggested (Longoni et al., 2013; Manotas Duque and Rivera Cadavid, 2007; Resta et al., 2016). Instead, companies with a sound operational and financial performance are more prone to invest in social programs related to their workforce and communities (Orlitzky et al., 2003; Sadeghi et al., 2016; Wang, Lu, et al., 2016). Also, some theories suggest that some indicators of EP, such as pollution and noise reduction, lead to improved SP in the form of employee safety and communities wellbeing (Distelhorst et al., 2017; Galeazzo et al., 2014). Therefore, as presented in Figure 19, hypothesis 1 suggests that there is a stronger indirect effect of LM on SP through EP and OP.

Although a direct path from OP to SP could also be plausible, in the presence of LM, operational gains can lead to undesirable social effects, which contravenes the cumulative approach proposed in this hypothesis. As an example, standardized tasks could be detrimental of job satisfaction (Solaimani and Sedighi, 2020), automation of processes and improved OEE can lead to redundant workplaces (Azuan et al., 2017; Manotas Duque and Rivera Cadavid, 2007), and flexibility achieved through cross-training could lead to increased occupational risks and job-instability sensation (Bergenwall et al., 2012; Longoni et al., 2013). Therefore, the direct relationships between OP and SP will be studied under hypothesis 2. Then, hypothesis 1 will be proposed as follows:

H1: “*Lean manufacturing effects on each pillar of sustainable performance are cumulative and follow a sand-cone model with operational performance at the base*”

2.3.2. Hypothesis 2: trade-offs approach

The trade-offs concept has been always present in nature. Water running down a dam is trading potential energy to kinetic energy. An athlete running the 100 meters sacrifices endurance in favor of raw speed. However, in manufacturing and business, companies are not too keen to let go one competitive priority. However, as manufacturing and customer demands become more specialized, some level of trade-offs is inevitable between cost, quality, customization, and delivery (Skinner, 1969; Vivares-Vergara et al., 2016). Regarding sustainable performance, the trade-offs concept has been also extended to the three pillars of TBL (Lai et al., 2013).

This second hypothesis proposes that those trade-offs are present between all three (or at least two) pillars of TBL performance during the implementation of LM. In other words, the allocation of resources required to pursue LM principles and implement its practices and tools, will inevitably collide with the allocation of resources required for environmental and social programs. This assumption is derived from theoretical insights presented in the following paragraphs. Trade-offs in OM research are commonly evaluated from a multi-objective optimization perspective. Tayyab et al. (2018) employed Weighted Fuzzy Goal Programming (WFGP) to evaluate the possible trade-offs between cost and carbon emissions in regard to the production lot size, in the presence of LM. Xiao et al. (2021) used a similar approach to determine the best machining sequence to address the trade-offs between energy consumption and cost, to obtain a sustainable manufacturing process. System dynamics has also been employed to address trade-offs, mainly given the complexity associated with sustainability measures (Solaimani and Sedighi, 2020). However, according to Velásquez Rodríguez and Moreno Mantilla (2017), the system dynamics approach can present limitations when evaluating the relationships between multiple supply-chain members. Therefore, they propose the use of Agent-Based Simulation (ABS) to study the emergence of trade-offs between economic and environmental outcomes in a reverse logistics chain.

Optimization algorithms and simulation techniques are useful when dealing with trade-offs, as they allow to evaluate multiple scenarios providing data for a more straightforward decision-making process on how to deal with them (Bonilla et al., 2018). However, the objective of this research (in regard to the second hypothesis) is to evidence if trade-offs manifest in the data sample. For this reason, a novel approach in OM to test for such trade-offs will be employed, based in the use of non-recursive SEM (Arbuckle, 2014). This implies that the one-way weight of the effect of one construct (i.e. the three TBL pillars) into another can be different than the effect in the opposite direction. If at least one pair of effects have different signs (positive in one direction, and negative in the other) it will prove the trade-offs hypothesis. The use of non-recursive SEM models to prove trade-offs have been previously employed in other fields of science, especially in ecology (Pratt et al., 2021; Shipley et al., 2006), economy, and healthcare management (Harris, 2006). The structural non-recursive model for hypothesis 2 is represented in Figure 20.

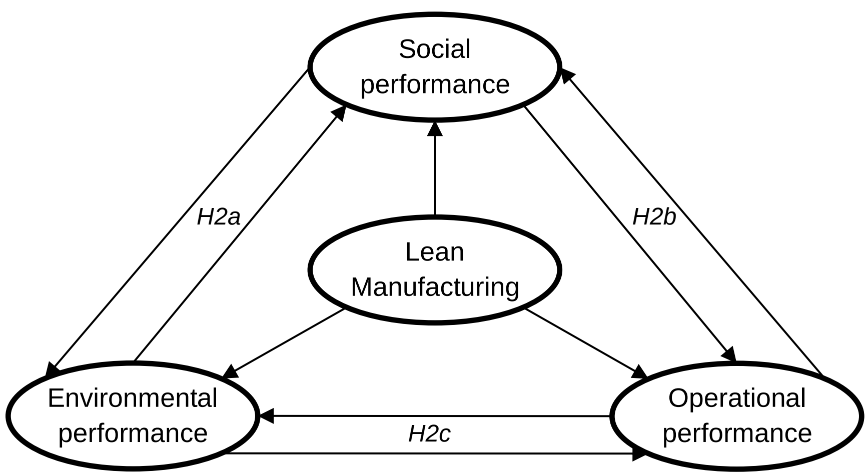

Figure 20. Hypothesis 2 structural model

When Elkington proposed the TBL approach to sustainability, it was seen as a win-win-win scenario in which a desirable level of performance could be achieved in all dimensions. However, there has been growing concerns regarding that this is not universally achievable, and that effectively trade-offs do occur between economic, environmental, and social dimensions (Ciccullo et al., 2018; Figge and Hahn, 2012; Gong et al., 2018; Martínez León and Calvo-Amodio, 2017). As presented in Table 13, most of those trade-offs have been identified between operational and environmental dimensions in presence of LM, while only the work of Resta et al. (2017) presents also some social trade-offs.

It is hard to question that operational performance awareness is present in every manufacturing operation (as economic performance is present in every company), however, environmental and social performance are not necessarily closely followed by each company (Busse, 2016). This favoring of operational, and ultimately economic, outcomes implies that managers will ultimately face trade-offs between financial expectations from shareholders, and environmental and social expectations from other stakeholders. OM research is called to provide alternatives for addressing those implicit trade-offs without excessively affecting each single pillar (Ciccullo et al., 2018).

Table 13. LM operational and environmental trade-offs

Aspect	Lean Goals	Environmental Goals
JIT deliveries	Increase delivery frequencies	Decrease carbon emissions with transport consolidation and routing planning
Lot size reduction	Reduces lot size to increase flexibility	Optimize lot size to reduce waste
Customer satisfaction	By cost and lead-time reduction	By environmentally friendly products
Waste focus	Manufacturing waste (mudas) minimization	Carbon footprint minimization
Supplier selection	Supplier delivery performance and quality	Green supply chain
Performance focus	Maximize operational performance	Minimize resource utilization

Adapted from: (Bergenwall et al., 2012; Busse, 2016; Fahimnia et al., 2015; Hartini and Ciptomulyono, 2015; Martínez León and Calvo-Amodio, 2017; Resta et al., 2017; Thanki et al., 2016)

Pagell and Shevchenko (2014) suggest that the trade-offs perspective is often found because the management research approach of “does it pay to be sustainable?”, implies that environmental and social outcomes must be reduced to profits (or losses). Therefore, companies focus on both social and environmental practices which don’t harm long-term economic performance (Dey et al., 2020). A complementary explanation for the observed trade-offs could be that the resources required to continue driving OP, EP, and SP start to compete against each other (Thomas et al., 2016), and their allocation leads to different levels of performance for each pillar. From a different perspective, Martínez León and Calvo-Amodio (2017) also suggest that some environmental regulations can compromise the implementation of some lean practices which could be harmful to operational performance.

Trade-offs between sustainability indicators in the presence of LM were evidenced in a multi-case study by Bergenwall et al. (2012). They concluded that frequent transportation derived from smaller lot sizes and JIT deliveries improved operational indicators such as WIP and flexibility but resulted harmful to the environment in the form of increased green-house gas emissions due to more frequent transportation. A later study by Fahimnia et al. (2015) provided empirical evidence to confirm Bergenwall et al. (2012) suggestions, but also included waste reduction and energy use among the considered environmental outcomes. Their work also considered a comprehensive study of the lean-green relationships across three stages of the supply chain (production, distribution and warehousing), concluding that lean trade-offs with environmental indicators are less likely in the production stage, and more likely in the distribution and warehousing stages.

Solaimani and Sedighi (2020) employed system dynamics to analyze the interrelationships between LM and TBL dimensions on the construction industry. Their results were obtained from a SLR which pointed to most cases of lean practices having a reinforcing effect on TBL dimensions (which points to hypothesis 1). However, they also evidenced trade-offs which mostly seem to materialize between economic (and operational) and non-economic dimensions, with improved manufacturing output resulting in negative effects to the workforce, such as less job opportunities. This is consequent with Kravchenko et al. (2020) SLR conclusions. They state that trade-offs are inherent to sustainability and provide basic criterions for companies to deal with such trade-offs. However, their review does not cover the role that LM can have in producing (or dealing) with such trade-offs.

Although other authors do not specifically mention the trade-offs perspective, their findings suggest that at different levels of LM implementation, performance can be affected in one or more of the three pillars. Sonntag (2000) was the first to raise the concern that, as advanced manufacturing technologies (which by her definition include LM) can improve operational performance by means of shorter lead-times and faster time to market, they could lead to increased resource consumption in the long-term in order to sustain the shorter product lifecycle dynamic. This claims are also supported by pollution and traffic concerns derived from JIT deliveries and employees fears of job instability from cross training programs (Bandehnezhad et al., 2012; Martínez León and Calvo-Amodio, 2017; Resta et al., 2017). Adverse findings were also noted by Silva et al. (2013), claiming that LM is an effective driver for productivity, and that becomes the most relevant factor for the workers involved, while "*the main effects of LM on environmental and social sustainability turned out to be directly related to the reduction of cost*". Therefore, the second hypothesis is proposed as follows:

H2: "*Lean manufacturing implementation leads to trade-offs between the three pillars of sustainable performance*"

2.3.3. Operationalization of hypotheses

At the end of Sections 2.3.1 and 2.3.2 both proposed hypotheses are derived from the state-of-the-art and presented in the form of "research hypotheses". This means that those are the conceptual propositions that are intended to be proven (or rejected) by analyzing the collected data. However, as this research will rely on structural equation models (SEM) for the statistical data processing, an operationalization of the hypotheses is presented in Table 14, in accordance with Figure 19 and Figure 20. This implies the decomposition of the main hypothesis (i.e. the "research hypothesis") in a series of sub-hypothesis that can be subsequently tested using the results from the SEM analysis.

Table 14. Operationalization of SEM hypotheses

Research hypothesis	Sub-hypothesis	Operationalization
Hypothesis 1	*H1a*	Lean manufacturing has a positive effect on operational performance
	H1b	Operational performance has a positive effect on environmental performance
	H1c	Environmental performance has a positive effect on social performance
	H1d	*Lean manufacturing has a positive effect on environmental performance (alternative)*
	H1e	*Lean manufacturing has a positive effect on social performance (alternative)*
Hypothesis 2	*H2a*	The non-recursive relationship between environmental performance and social performance in the presence of LM has a positive and negative effect
	H2b	The non-recursive relationship between social performance and operational performance in the presence of LM has a positive and negative effect
	H2c	The non-recursive relationship between environmental performance and operational performance in the presence of LM has a positive and negative effect

According to the operationalization of Table 14, hypothesis 1 will be proven if *H1a*, *H1b*, and *H1c* result valid for the data sample, therefore, validating the hypothesized "sand-cone" model. *H1d* and *H1e* are presented as alternative hypothesis. Therefore, if *H1d* and *H1e* are also valid on the data sample, hypothesis 1 will be proven as long as the indirect effects of LM on environmental and social performance are greater than the direct effects (*H1d* and *H1e*). Consequently, hypothesis 2 will be proven if *H2a*, *H2b*, and *H2c* are true, confirming the "trade-offs" model. However, as the hypothesized trade-offs does not necessarily have to manifest among all TBL pillars, the validation of *H2a* or *H2b* or *H2c* alone could present evidence of trade-offs between the corresponding sustainable performance dimensions.

2.4. Operationalization of variables

As Section 2.3 states, this research deals with the relationship between two main variables: Lean Manufacturing (LM), and Sustainable Performance (SSTP), with the former considered as independent variable, and the latter dependent variable. Since both variables are not directly observable and quantifiable, they will be considered as latent variables (or constructs), which mean that each one of them is reflected in several measurable variables (or predictors) (Khanchanapong et al., 2014; Nawanir et al., 2018). This system of observed values and its dependency of unobserved variables is called "Measurement Model" (Arbuckle, 2014) in SEM analysis.

The proposed indicators and constructs were collected according to the state of the art available in scientific literature, and empirically validated through qualitative (case study) and quantitative (confirmatory factor analysis) methods, in order to filter inconsistent variables (Losonci et al., 2017) and obtain an acceptable construct validity, or in other words, guarantee that the proposed set of measured variables, actually represent the theoretical latent construct that they are designed to reflect (Hair et al., 2009).

It's important to mention that although no unified or widely accepted assessment methods exists for both lean manufacturing and sustainable performance, several metrics have been previously used in literature for measuring each studied dimension. Different sets of indicators, measures, variables, and other assessment tools were collected from literature and grouped into bundles of metrics in different categories, aiming for four essential parameters: comparability, reliability, relevance, and measurability (Zhang et al., 2017). Additionally, the proposed metrics and bundles are consequent with the theoretical approach presented in Chapter 1, and the methodology in Chapter 2, while also meeting important practical considerations such as being action-oriented, concise, easily communicated, easily understood, and methodologically sound (Narayanamurthy and Gurumurthy, 2016b; Shahbazi et al., 2018).

The proposed survey is constructed gathering variables from previous research which properly reflect the two main constructs (lean manufacturing level of implementation and sustainable performance). An important distinction must be made between measures, metrics, and indicators. A measure is a value obtained relative to a defined standard. A metric places multiple measures in a context that allows them to be compared. Finally, an indicator compares a metric to a baseline, or a previously set goal, in order to assess its progress or achievement (Sutherland et al., 2016). The proposed framework of variables presented in the next sections, which comprise the data collection instrument (i.e. survey) is therefore based on metrics.

2.4.1. Lean manufacturing

Several methods have been proposed for assessing the level of lean manufacturing implementation in a given company (Pakdil and Leonard, 2014). According to a recent literature review by Danese et al. (2018), no fewer than 14 academic papers have been published in the last decade regarding the assessment of the degree of lean implementation, and the development of models, indexes, and measures to assess lean adoption in manufacturing and service operations. In spite of multiple efforts to propose an universally (or at least widely) accepted assessment method or tool, there has been little consensus around how to properly measure the degree of LM implementation (Nawanir et al., 2018; Oleghe and Salonitis, 2016), most probably because of the intrinsic complexity of the matter, and the methods employed.

Susilawati et al. (2015) associate the complexity of lean assessment to three factors: first, the multi-dimensional nature of lean. Second, the unavailability of databases that allow benchmarking of different manufacturing practices; and third, the subjectivity of human judgment while evaluating the application and effectiveness of lean practices. Narayanamurthy and Gurumurthy (2016b) preformed a comprehensive SLR on "leanness" assessment, concluding that "*such diverse assessment methodologies available in literature have created complexities and also confusion among both the practitioners and academicians when they have to choose a suitable assessment method for a real-time study*".

One of the first unified sets of variables employed for LM assessment was proposed by Shah and Ward (2003), with valuation of different aspects of manufacturing practices, forming four sets of lean "bundles", namely TPM, TQM, HRM, and JIT. According to that framework, the "leanness" level of a company should be reflected on their performance on each of these bundles. This approach has been widely employed in subsequent research, by other notable works (Bortolotti, Danese, et al., 2015; Dal Pont et al., 2008; Furlan et al., 2011; Thanki et al., 2016), although, with the evolution of the lean concept and practices, other bundles have been proposed in addition to the four original ones.

A commonly encountered problem with the assessment of LM implementation through bundles of practices (in other words, evaluating the level of implementation of different practices in order to construct a lean "score" for a given company), relies on the fact that practices are implemented by companies on a need-to basis according to many context variables, which means that not necessarily all companies pursuing lean should implement the same practices or tools. This claim is supported by Oleghe and Salonitis (2016) who stated that "*LM is a philosophy and so the practices are not concrete objects, but there are metrics or Key Performance Indicators (KPIs) that are used in tracking the success of lean initiatives*". More recently, Nawanir et al. (2018) also claimed that "*most of the practitioners only used their own measurement instrument to portray the current status of their own manufacturing system, without emphasizing whether or not their systems have met the principles of LM itself*".

Other problem is that measuring the level of implementation of a given set of practices, not necessarily reflects on having the expected performance level (Narayanamurthy and Gurumurthy, 2016b). In other words, two companies that have implemented a lean practice, such as Kanban, not necessarily will lower their inventory levels in the same proportion, and even, one of them can be actually getting adverse results. This can be explained because often, in order to successfully implement LM, companies need to develop an unique approach to lean tools which, in some cases, become tailor-made for a specific context, culture, or market (Netland, 2016). This creates a practical difficulty for LM assessment methods that rely only on measuring the implementation of practices and tools without considering the underlying principles of those practices (Abobakr and Abdel-Kader, 2017; Bergenwall et al., 2012; Nawanir et al., 2018), as it was widely exposed in sections 1.3.2. and 1.3.3.

Instead of seeing LM just as a set of manufacturing tools that are either implemented or not in order for a company to become lean, other proposed assessment methods combine qualitative or perceptive (such as interviews and expert ratings) and quantitative approaches (Khalaf Albzeirat, 2018; Narayanamurthy and Gurumurthy, 2016b; Oleghe and Salonitis, 2016). This trend becomes more prone to the evaluation of the adherence to lean principles, rather than the implementation of single practices or bundles of them, as it is more difficult to quantify principles and cultural aspects due to their complexity and multidimensionality (Farias et al., 2019). Nevertheless, when the lean level of a company is assessed from the perspective of which are the main guidelines of their operations strategy (i.e. their principles) and how they concur with the lean concept and principles, a more deeply understanding and comparability can be achieved (Abobakr and Abdel-Kader, 2017).

The above statement is explained because lean tools evolve and adapt to each context and culture (Farias et al., 2019), therefore, tools and methods can be often different (losing comparability), but they are supposed to still pursue the same goal. As Netland (2016) states "*Tools and methods are effective and necessary for succeeding with the implementation of lean in a plant, but they are not sufficient on their own*". In fact, it often happens that popular lean practices are not known by operators of companies implementing lean (Losonci et al., 2017), and in other cases even managers are not fully aware of the aim of lean tools being employed (Abolhassani et al., 2016), a claim complemented by Alefari et al. (2017) statement that "*Although there is a wide assumption that through the use of lean tools and methods, lean manufacturing can be implemented; the reality is that these are not assuring success unless top management and leadership are tailored to the needs of lean manufacturing*".

More recently, fuzzy logic approaches to lean assessment have been proposed, most notably by Pakdil and Leonard (2014), but also by other authors (Matawale et al., 2015; Oleghe and Salonitis, 2016; Ben Ruben et al., 2017; Susilawati et al., 2015; Vinodh and Vimal, 2012), in an attempt to incorporate both qualitative and quantitative aspects into a single LM assessment framework. Although the fuzzy logic approach is supposed to help overcome problems like vagueness, uncertainty and ambiguity (Vinodh and Vimal, 2012), such assessment methods remain complex to implement by companies into their day-to-day decision making processes (Azadegan et al., 2011), and most literature applications rely on simulations and single case studies. In fact, Khalaf Albzeirat (2018) literature review claims that only 8% of studies assessing lean manufacturing referred fuzzy logic methods, a number slightly below the 26% claimed by Narayanamurthy and Gurumurthy (2016b).

Considering that the data collection instrument designed for this research is to be employed in the context of Colombia metalworking industry, some important considerations were taken. First, Colombia is considered a developing country and its industrial grid is mainly formed by SMEs with a medium technological level (Lesmes, 2017). Second, Colombian metalworking industries are usually not clustered around specific sectors or markets (Carranza Romero et al., 2018), but instead are sparse across multiple manufacturing fields such as electric machinery, boilers, automotive parts, aluminum manufactures, steel and iron manufactures, hand tools, shipyard, and many others (Camara de Comercio de Cali, 2018; Orozco and Aguirre, 2014). Third, Colombian context and culture clearly differs from eastern cultures where most of LM practices trace their roots. Even with a culture more related to European and North American countries (where lean practices and tools have evolved in the past years, prior to being "imported" to Colombian industry), cultural and organizational differences are still sound. The third point is specially worth noticing because organizational culture and HRM related aspects are one of the most influential factors in the developing of any manufacturing strategy (Vivares-Vergara et al., 2017), including LM implementation (Bortolotti, Boscari, et al., 2015; Čiarnienė and Vienažindienė, 2014; Henao et al., 2019).

According to Porter[5], is not countries who compete against each other, but companies. However, as Francica (2008) suggests, "*the definition of new strategies that allow Colombian society to achieve higher economic development rates and social welfare, need to be in accordance with new global trade trends, and the country own internal conditions*". Therefore, in order to obtain a better understanding of the studied phenomenon (i.e. effects of LM on sustainable performance), and comparability of the data gathered through the collection instrument, the selection of variables and first order constructs (that reflect the LM implementation level), and survey design will be developed following a mixed approach from previous research on the field.

The proposed observed variables (i.e. predictors or survey items) do not directly measure the level of implementation of a given lean tool or practice, since there is no guarantee (and no need at all) that all companies are employing the same lean tools. Instead, the instrument evaluates the level in which the company is pursuing lean objectives (in line with lean principles) using a single or several practices. This approach helps overcoming several previously pointed problems of lean assessment from the purely tools approach, while being more user-friendly to the respondent, as not necessarily all persons are familiar with the same tools (or are implementing them in their companies), but they should have a clearer idea of the goals they are pursuing with their manufacturing strategy.

In other words, the idea behind the conception of the data collection instrument is to ask companies if they are systematically applying different practices or tools (without naming a specific one) in order to achieve a set of concrete goals, that were previously identified as lean goals from the state-of-the-art review. In this way, it also helps to overcome one of most common difficulties of putting LM into practice, which, in the words of Hallam and Keating (2014) is described as "*the problem of failed lean transformations has generally been attributed to a focus on lean tools versus a focus on the underlying lean operational philosophy of the company*", a notion later supported by Nordin and Belal (2017) claim that "*the misunderstanding of the concept leads to various major issues such as piecemeal adoption of lean tools and techniques, misapplication of lean tools, and lack of lean culture development that support the lean manufacturing in the organization*".

Measurement models used for SEM analysis can be either reflective or formative (Abdul-Rashid et al., 2017; Davcik, 2014). In a formative model, each latent (i.e. unobserved) variable is "formed" by a series of indicators that completely describe the construct that they intend to measure (Solaimani et al., 2019). This pose a practical difficulty (especially in OM and social sciences research) since the researcher has to make the assumption that all measured items that describe the latent construct are indeed considered, otherwise, the underlying essence of the latent variable will be altered (Bagozzi and Yi, 2012). In other words, if an indicator is removed (or not considered) in a formative construct, the theoretical definition of the construct will be changed. In the case of the LM measurement model on Figure 21, and in that of the sustainable performance model presented later in Figure 23, reflective constructs will be employed.

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[5]Porter, M.E. (1990), "The competitive advantage of nations", Harvard Business Review, No. 2, pp. 182–204.

In addition to the practical caveats of formative constructs explained before, there are three important methodological justifications for the use of reflective constructs in the proposed research set-up. First the conception of reflective constructs is coherent with the *critical-realism* ontological position of the research. In the words of Iacobucci (2010), the philosophy behind reflective constructs is "*essentially Platonic: the unobservable was the ideal, pure form, and the observed was a combination of the ideal and imperfections. Translating to our purposes, the unobservable, or latent factor was reflected in the observed, measured variables, and those variables were also affected by noise, in the form of systematic and random errors*". Second, reflective constructs are consequent with the preferred statistical method in this case, which is the covariance-based SEM, as opposed to partial least squares SEM commonly employed with formative constructs. Since the objective of this research is to determine if some a-priori proposed models are valid (i.e. "fit" the collected data), the covariance-based SEM approach used by AMOS software fulfill this purpose (Davcik, 2014; Solaimani et al., 2019).

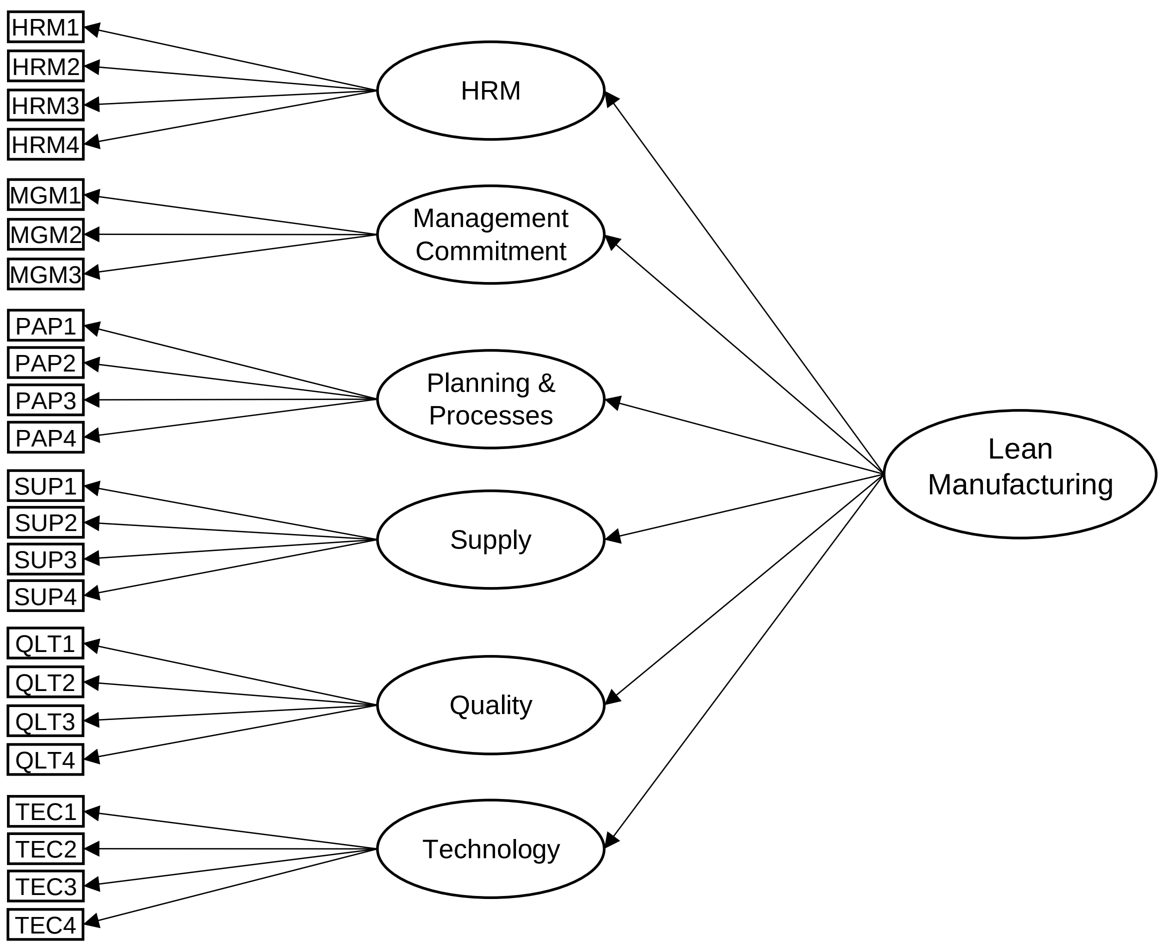

Figure 21. Lean manufacturing construct

Finally, the studied constructs (LM implementation level and sustainable performance) are not physical entities that can be directly measured, but instead are a theoretical conception of a given set of premises (hence the term "latent" variables) that can manifest (reflect) in several measurable indicators (Solaimani et al., 2019). As those theoretical conceptualizations are assumed to have an inherent level of subjectivity (associated to the definition of "*what it is to be lean?*", and "*what it is to have sustainable performance?*"), it is possible that the measured variables (i.e. indicators) are a consequence of multiple causes (i.e. latent constructs). Such indicators need to be eliminated from the model to prevent cross-loading (multiple constructs being reflected in the same indicator), without altering the theoretical conceptualization of the constructs (Katiyar et al., 2018; Shook et al., 2004). That's why "*management measures in self-reporting studies are based almost exclusively on creating a scale that is assumed reflective*" (Davcik, 2014).

In line with the common practice in LM empirical research, observed variables are grouped in bundles, which were derived from the state-of-the-art reviewed in the theoretical framework. In this way, the independent variable, which is the level of lean manufacturing implementation becomes a second order reflective latent construct (in line with the SEM methodology defined), composed by a series of first order reflective latent constructs, representing the different bundles comprising the main aspects on which the implementation of lean practices and tools (and ultimately, the pursuing of the lean philosophy) should reflect. Finally, the first order constructs are reflected on the observed variables, as presented in the above paragraphs, and pictured in Figure 21. Each bundle will be described and supported in the following paragraphs. In the same way, the observed variables, are presented in the form of survey questions, with their corresponding theoretical support. Finally, Table 15 summarizes the survey questions comprising each lean bundle, with their referring literature. Since the instrument is to be applied to a sample of Colombian metalworking industries, Table 15 also includes the Spanish translation of each question.

- **Human Resources Management:** since Shah and Ward's (2003) seminal work, practices that focus on HRM have been considered one of the most important lean bundles. This is because lean practices have evolved mostly into "soft" practices (Cherrafi et al., 2016; Danese et al., 2018; Nordin and Belal, 2017), which means that they rely heavily on people's commitment to achieve lean goals, rather than in new machinery or cutting-edge technology (Bortolotti, Boscari, et al., 2015). In fact, HRM practices are well in-line with at least 4 of Liker's (2004) TPS principles presented in Table 2.

Human resources management practices related to lean manufacturing point to four main objectives. First, promote a continuous improvement culture (Bortolotti, Danese, et al., 2015; Cherrafi et al., 2016; Dal Pont et al., 2008; Dombrowski and Mielke, 2013; Nordin and Belal, 2017; Ben Ruben et al., 2017). Second, promote leadership and empowerment of work teams to autonomously and quickly solve problems (Narayanamurthy and Gurumurthy, 2016a; Resta et al., 2017; Sajan et al., 2017; Shah and Ward, 2003). Third, create a clear definition of tasks and roles (sometimes called "job design") with standardized training processes (Shah and Ward, 2003; Vinodh and Vimal, 2012); and fourth, develop multi-skilled personnel with cross-training capabilities (Bergenwall et al., 2012; Dal Pont et al., 2008; Resta et al., 2017; Shah and Ward, 2003).

- **Management Commitment:** management commitment is crucial to a successful LM implementation (Negrão et al., 2017; Netland, 2016), or put in other words, lack of management commitment and has been identified by several authors as one of the causes of lean failure (Azuan et al., 2017; Čiarnienė and Vienažindienė, 2014; Taleghani, 2010). As Gobinath et al. (2015) state, "*if management principles are fully integrated with shop floor principles, then lean systems can be applied efficiently to attain the maximum output*". In spite of the clear consensus around the matter, early lean empirical studies (such as Dal Pont et al. (2008) and Shah and Ward (2003)) scarcely considered lean practices related to management and their alignment to strategy. However, most recent research has begun to consider variables relating the coherence between business strategy and manufacturing strategy (which includes LM), an important part of LM implementation assessment (Matawale et al., 2015; Negrão et al., 2017).

Critical management and strategic factors that reflect on the success (or failure) of lean manufacturing implementation can be gathered into three topics: alignment between manufacturing strategy and business strategy (Matawale et al., 2015; Narayanamurthy and Gurumurthy, 2016a; Vinodh and Vimal, 2012); top-management driven 5S culture (Abolhassani et al., 2016; Bortolotti, Danese, et al., 2015); and, clear efforts to eliminate non-value-added activities at all organizational levels and processes (Belekoukias et al., 2014; Farias et al., 2019; Helleno et al., 2017; Matawale et al., 2015). The importance of considering this aspects as part of the lean level assessment, is that, while a company can have a high level of implementation of some lean practices, their success and sustainability can be severely jeopardizing if the three above mentioned topics are not present (Abolhassani et al., 2016; Cherrafi et al., 2016; Netland, 2016).

• **Planning and processes:** standardization and continuous process flow have been pillars of lean manufacturing and previous modern manufacturing systems like TPS (Liker, 2004; Womack et al., 1990). This have led to different practices and tools gathered around what Shah and Ward (2003) dubbed the JIT bundle. JIT practices aim to achieve a streamlined process flow with balanced operations, through tools like one piece flow, cellular manufacturing, levelled production, and pull systems (Belekoukias et al., 2014; Marodin et al., 2019; Ben Ruben et al., 2017). However those practices need to be accompanied by specific planning criterions and tools (such as small lot sizes, advanced ERP systems, and daily scheduling), that allow them to perform at their best (Bortolotti et al., 2013; Khanchanapong et al., 2014; Shah and Ward, 2003; Vinodh and Vimal, 2012).

Although some researchers have gathered JIT practices focused on manufacturing with those focused on supply into a single bundle or construct, for the purpose of the present research process related practices are considered a separate bundle from supply related practices. As Martínez-Jurado and Moyano-Fuentes (2014) pointed out, “lean supply chains” have significant differences from traditional supply chains. However, achieving lean goals in supply does not necessarily guarantee achieving other production-related lean goals, and vice versa (Bhamu et al., 2014; Moyano-Fuentes et al., 2019). Therefore, a company with a high level of “leanness” in their production processes, would probably boost its benefit in overall performance if it has a lean supply chain (Belekoukias et al., 2014), creating the need to assess both aspects separately.

A total of four lean planning and process goals are considered in the proposed survey: lot size reduction (Abolhassani et al., 2016; Fullerton et al., 2014; Shah and Ward, 2003); standardized and continuous process flow (Marodin et al., 2019; Narayanamurthy and Gurumurthy, 2016a; Shah and Ward, 2003; Tortorella et al., 2017); short-term, demand-driven (pull) production planning (Marodin et al., 2019; Matawale et al., 2015; Vinodh and Vimal, 2012); and, WIP inventory reduction (Khanchanapong et al., 2014; Narayanamurthy and Gurumurthy, 2016a; Oleghe and Salonitis, 2016).

• **Supply:** as stated and justified in previous paragraphs, lean manufacturing processes need lean supply practices in order to maximize performance of the whole lean system. In fact, the supply network has been considered since the original TPS principles presented by Liker (2004). Even in the nineties, Womack et al. (1990) also noticed how lean companies like Toyota focused their efforts on having a considerably smaller supplier network while helping them to grow together and sharing their principles, achieving a win-win situation. Instead, most American manufacturers (like GM and Ford) forced many suppliers to constantly compete against each other while imposing on them unachievable cost-reduction goals, that ultimately, result in the supplier sacrificing quality, delivery, or other performance measures, or simply, handing over the business.

Although lean supply chains have been a topic of growing interest in recent academic literature, this research is focused on lean manufacturing. Hence, not all aspects of lean supply chain addressed in literature will be evaluated trough the survey, but only the topics that are deemed necessary for a successful LM implementation. In total, four mayor aspects are considered: Use of pull systems to achieve a demand-driven low inventory supply (Khanchanapong et al., 2014; Matawale et al., 2015; Shrafat and Ismail, 2019); supplier development for long-term win-win relationship (Abolhassani et al., 2016; Jasti and Kodali, 2015; Martínez-Jurado and Moyano-Fuentes, 2014; Tortorella et al., 2017); quality as the main supplier selection criteria (Moyano-Fuentes et al., 2019; Narayanamurthy and Gurumurthy, 2016a; Pakdil and Leonard, 2014); and, supplier involvement in new product development and improvement (Bortolotti, Danese, et al., 2015; Narayanamurthy and Gurumurthy, 2016a; Pakdil and Leonard, 2014).

• **Quality:** operations management after the second world war followed (in most cases) a trade-offs approach in western hemisphere (Bortolotti, Danese, et al., 2015), until the late XX century. This means that, in order to gain advantage in a given competitive priority (i.e. cost, quality, delivery, service, innovation, or flexibility), the others needed to be sacrificed (Gomez et al., 2017; Sarache Castro et al., 2007). In other words, a better cost performance came at the expense of quality. However, this paradigm was contested by LM (mainly developed in the eastern hemisphere), and in fact, was one of the most noted differences between traditional and lean manufacturing systems (Womack et al., 1990); which managed to obtain considerably lower defect rates than their American counterparts, while having also increased flexibility, lower lead-times, and competitive costs (Bhamu et al., 2014).

Since the beginning, quality improvement and management has been intrinsic to the lean concept (Danese et al., 2018). Shah and Ward (2003) gathered practices specifically oriented to quality into the TQM bundle, and from then, quality related goals, tools, and practices have been considered in most empirical research on LM (Bhamu et al., 2014). According to Singh and Ahuja (2012), the TQM concept comprises three important concepts: “total”, since it requires the involvement of the whole company; “quality”, as exceeding the customer expectations; and “management” as the systematic commitment to quality leadership.

For this research, the quality construct should reflect in four aspects: exceeding customer expectations (Matawale et al., 2015; Narayanamurthy and Gurumurthy, 2016a; Singh and Ahuja, 2012); use of SPC to reduce variability (Bhamu et al., 2014; Leguízamo-Díaz and Moreno-Mantilla, 2014; Shrafat and Ismail, 2019); available and updated quality performance information (Bortolotti, Danese, et al., 2015; Fullerton et al., 2014); and, top management commitment to quality (Bortolotti, Danese, et al., 2015; Matawale et al., 2015).

• **Technology:** many authors agree that LM is formed by a combination of interrelated “soft” (i.e. human centered) and “hard” (i.e. technology centered) practices (Bortolotti, Boscari, et al., 2015;

Danese et al., 2018). Best results of LM can be achieved by a synergistic implementation of both kinds, balancing the use of technology (purpose-built, reliable, proven, and state of the art), with proper training and culture. According to Chavez et al. (2015), "*organizations that work with state-of-the- art technologies may be able to obtain competitive advantage through fast technological innovation; however, competitive advantage is only a temporary advantage since product obsolescence occurs more quickly in these fast-pace technological environments*". Therefore, cutting-edge technology cannot guarantee a sustained performance. Instead, the goals and practices of the technological dimension of LM, need to be aligned with the "soft" goals and practices (Ortega Jimenez et al., 2015; Tortorella and Fettermann, 2018).

On the other hand, one of Liker's (2004) TPS principles calls for the use of reliable and proven technology, which also includes "hard" tools and techniques in order to enable the sustainability of the manufacturing system (Venugopal and Saleeshya, 2019). Such techniques, like SMED, have been discussed since early LM literature (Cherrafi et al., 2016; Farias et al., 2019), while they have also been complemented by more recent ones. Therefore, four main LM technology-related goals will be assessed with the proposed instrument: setup times reduction (Chavez et al., 2015; Jasti and Kodali, 2015; Marodin et al., 2019; Shrafat and Ismail, 2019); application of TPM principles (Abolhassani et al., 2016; Bortolotti, Boscari, et al., 2015; Shah and Ward, 2003; Tortorella and Fettermann, 2018); cellular manufacturing (Matawale et al., 2015; Pakdil and Leonard, 2014; Ben Ruben et al., 2017; Shah and Ward, 2003); and, constant monitoring and improvement of OEE (Belekoukias et al., 2014; Oleghe and Salonitis, 2016; Singh and Ahuja, 2012; Vinodh and Vimal, 2012).

It is important to consider that many of the selected studies in Table 15 draw their samples from secondary data, such as the high-performance manufacturing (HPM) survey and other inter-sector, inter-country, large-scale surveys. In such cases, the data gathering instruments are not purposely design for the measurement of the specific constructs, and the available indicators are "picked" to best represent the intended variables. In other cases, the questionnaires were purposely-design to assess LM implementation, but not necessarily in the same context, country, or in relation to the same dependent variable. Therefore, not all the available indicators in the selected studies were employed for the designed survey. Instead, indicators that were mostly common to the majority of the studies were selected, as long as they were coherent with the theoretical approach of the current research. To cope with the potential limitations of this selection, the complete survey was subsequently submitted to validity tests (Section 3.2), where a panel of experts assessed (among other variables) the sufficiency of the constructs and chosen indicators. The same reasoning applies to the sustainable performance variables described in Table 17.

Table 15. Lean manufacturing observed variables and survey questions

Bundle	Code	Lean goal / principle	Survey question	Spanish translation	References
Human Resources Management	HRM1	Promote a continuous improvement culture	We have a structured continuous improvement culture that involves all the company	Existe una cultura de mejora continua estructurada que involucra a toda la compañía	[1,4,5,7,8,9,10,12, 18,22,23,24,27,31,32]
	HRM2	Promote leadership and empowerment of work teams to autonomously and quickly solve problems	We have autonomous work teams empowered to solve most of first-level problems quickly without consulting with their supervisors	Existen equipos autónomos de trabajo empoderados para resolver la mayor parte de los problemas de primer nivel rápidamente sin consultar con sus supervisores	[4,5,13,15,16,18,22,23, 24,25,26,27,29,31]
	HRM3	Create a clear definition of tasks and roles with standardized training processes	There are standardized training programs for all personnel and tasks profiles are clearly defined according to the training level	Existen programas de entrenamiento estandarizado para todo el personal y los perfiles de las tareas se definen claramente de acuerdo al nivel de entrenamiento	[4,5,13,18,26,27,31]
	HRM4	Develop multi-skilled personnel with cross-training capabilities	Employees are trained to achieved multiple skills that allow them to perform multiple tasks in different workplaces	Los empleados se entrenan para desarrollar polivalencia que les permite desempeñar múltiples tareas en diferentes puestos de trabajo	[7,11,12,13,14,15, 16,18,19,22,24,25,29]
Management Commitment	MGM1	Alignment between manufacturing strategy and business strategy	Manufacturing strategy is clearly defined and aligned with organizational strategy, and it is deployed to all company levels	La estrategia de manufactura está claramente definida y alineada con la estrategia organizacional, y se despliega a todos los niveles de la compañía	[5,16,18,22,25,31,32]
	MGM2	Top-management driven 5S culture	We have a 5S culture at all company levels with full top-management commitment	Existe una cultura de 5S en todos los niveles de la compañía con compromiso directo de la alta gerencia	[1,2,3,5,8,9,10,12, 20,21,23,26,28,31,32]
	MGM3	Clear efforts to eliminate non-value-added activities at all organizational levels and processes	We apply VSM techniques to all critical processes and actively perform efforts to minimize non-value-added activities	Se aplican técnicas de VSM (mapeo de la cadena de valor) a todos los procesos críticos y se realizan esfuerzos permanentes para minimizar las actividades que no agregan valor	[1,3,8,10,11,12, 16,23,30,31,32]
Planning and Processes	PAP1	Lot size reduction	We apply efforts to reduce lot sizes for each product and manufacture just the exact quantities needed.	Se realizan esfuerzos para reducir los tamaños de lote de cada producto y fabricar solo la cantidad exacta requerida	[2,6,8,9,11,12,14,16, 18,19,22,24,27,31,32]
	PAP2	Standardized and continuous process flow	Process are defined and standardized in order to achieve continuous one-piece flow with high output rates	Existen procesos definidos y estandarizados con el fin de lograr un flujo continuo pieza a pieza con alta cadencia	[2,7,10,11,13,14,15, 20,21,22,23,28,30,32]
	PAP3	Short-term, demand-driven (pull) production planning	We use a short-term production planning with flexibility to quickly change the program in respond to actual demand during each month	Se utiliza un plan de producción de corto plazo con la flexibilidad de cambiar la programación en respuesta a la demanda real durante cada mes	[1,2,5,8,10,11,13, 14,15,16,18,19,22, 23,27,28,29,30,31]
	PAP4	WIP inventory reduction	Production planning and manufacturing system are organized in order to minimize the required WIP inventory	La planeación de la producción y el sistema de manufactura se organizan con el fin de minimizar el inventario requerido de producto en proceso	[2,5,9,12,14,16, 18,19,20,21,26,31]

Supply	SUP1	Use of pull systems to achieve a demand-driven low inventory supply	We are synchronized in real-time with our suppliers to receive materials according to production demand (pull system)	Se cuenta con una sincronización en tiempo real con los proveedores con el fin de recibir los materiales de acuerdo a la demanda de producción (sistema pull)	[4,5,10,13,16,17,19, 20,23,26,28,29,30,31]
	SUP2	Supplier development for long-term win-win relationship	We have supplier development processes focused on achieving long-term, win-win relationships	Existen procesos de desarrollo de proveedores enfocados en alcanzar relaciones gana-gana de largo plazo	[2,4,5,6,11,13,17, 19,20,23,26,29,30,31]
	SUP3	Quality as the main supplier selection criteria	Quality performance is considered the main criteria for selecting and evaluating suppliers	El desempeño de calidad se considera como el principal criterio para evaluar y seleccionar proveedores	[5,13,16,17,18,23,31]
	SUP4	Supplier involvement in new product development and improvement	Suppliers actively participate in new product development, and continuous improvement of current ones	Los proveedores participan activamente en el desarrollo de nuevos productos y el mejoramiento de los actuales	[5,6,11,17,18,19,20,23]
Quality	QLT1	Exceeding customer expectations	We are constantly surveying our customer needs and proactively doing efforts to exceed them	Constantemente evaluamos las necesidades de nuestros clientes y realizamos esfuerzos proactivos por excederlas	[5,6,13,16,18,22, 23,26,29,30]
	QLT2	Use of SPC to reduce variability	We control all our critical processes with SPC techniques to minimize variability	Controlamos todos nuestros procesos críticos con técnicas de SPC (control estadístico de procesos) para minimizar la variabilidad	[4,5,7,13,18,19, 22,23,24,27,28,29]
	QLT3	Available and updated quality performance information	Quality performance information is updated, visible, and readily available to all personnel	La información sobre el desempeño de calidad se encentra actualizada, visible, y disponible para todo el personal	[1,3,5,9,10,11,12, 14,15,19,20,42,29,32]
	QLT4	Top management commitment to quality	We have a quality management culture were all managers and employees accept their responsibility and commitment to quality	Existe una cultura de gestión de la calidad en la cual todos los administradores y empleados aceptan su responsabilidad y compromiso con la calidad	[1,4,5,11,16,18,22, 23,24,27,31]
Technology	TEC1	Setup times reduction	We are constantly doing efforts to reduce our set-up times	Constantemente realizamos esfuerzos para reducir nuestros tiempos de cambio de referencia	[1,2,3,8,9,15,19,20,21, 22,26,27,28,29,31,32]
	TEC2	Application of TPM principles	We extensively apply TPM principles and perform preventive, predictive, and autonomous maintenance activities	Aplicamos extensivamente los principios de TPM (mantenimiento productivo total) y se realizar actividades de mantenimiento preventivo, predictivo y autónomo	[1,2,4,5,8,10,14, 15,16,18,19,20,22,23, 24,26,27,29,31,32]
	TEC3	Cellular manufacturing	Our production system is configured in specialized flexible cellular manufacturing stations	Nuestro sistema de producción está configurado en células de manufactura especializada flexibles	[1,5,8,9,10,14,16,18,19, 20,22,23,24,27,31,32]
	TEC4	Constant monitoring and improvement of OEE	We constantly measure and monitor OEE performance (downtimes, cadence, quality) and use it as a decision-making parameter	Mantenemos un monitoreo y medición constante del OEE (tiempos de paradas, cadencia, calidad) y se utiliza como parámetro de toma de decisión	[6,10,13,14,16,21,31]
[1]Abobakr and Abdel-Kader, 2017; [2]Abolhassani et al., 2016; [3]Arrieta et al., 2011; [4]Bortolotti, Boscari, et al., 2015; [5]Bortolotti, Danese, et al., 2015; [6]Chavez et al., 2015; [7]Dal Pont et al., 2008; [8]Farias et al., 2019; [9]Fullerton et al., 2014; [10]Garza-Reyes et al., 2018; [11]Jasti and Kodali, 2014, [12]Khalaf Albzeirat, 2018; [13]Khanchanapong et al., 2014; [14]Manotas Duque and Rivera Cadavid, 2007; [15]Marodin et al., 2019; [16]Matawale et al., 2015; [17]Moyano-Fuentes et al., 2019; [18]Narayanamurthy and Gurumurthy, 2016, [19]Nawanir et al., 2018; [20]Negrão et al., 2017; [21]Oleghe and Salonitis, 2016; [22]Ortega Jimenez et al., 2015; [23]Pakdil and Leonard, 2014; [24]Raj et al., 2017; [25]Resta et al., 2016; [26]Sajan et al., 2017; [27]Shah and Ward, 2003; [28]Shrafat and Ismail, 2019; [29]Tortorella et al., 2017; [30]Tortorella and Fettermann, 2018; [31]Vinodh and Vimal, 2012; [32]Zhou, 2016					

2.4.2. Sustainable performance

Measuring performance is a complicated task at any business level (Hubbard, 2009). Objectivity, comparability, reliability, relevance, understandability, measurability, and long-term orientation of any performance metric are important concerns that managers should be aware of (Zhang et al., 2017). Souza and Alves (2018) claim that "*performance indicators reveal what has happened and what will happen; they provide information to support decision-making, potentially affecting the future competitive position of the organization*". Measuring sustainable performance becomes an even more complicated task because of the multi-dimensional nature of sustainability, the need to measure both quantitative and non-quantitative aspects (Burritt and Schaltegger, 2014), and the subjectivity associated with many non-economic measures (Dočekalová and Kocmanová, 2016; Pagell and Shevchenko, 2014).

As exposed in Section 1.4, most OM academic research on sustainability address the development of frameworks and strategies to include sustainability concepts and practices into manufacturing operations (Kowang et al., 2016; Martínez León and Calvo-Amodio, 2017; Ocampo and Estanislao-Clark, 2014; Pham and Thomas, 2011). In lesser extent, some papers present frameworks for sustainability assessment (Gualandris et al., 2014; Ketokivi and Schroeder, 2004; Reich-Weiser et al., 2008). Nevertheless, there has been a lack of consensus regarding the best way to address the sustainability concept in manufacturing operations (Resta et al., 2017; Wang, Hsu, et al., 2016), and furthermore, the best way to assess the sustainable performance of a given company (Hubbard, 2009; Souza et al., 2018).

In fact, as Ciannella and Morioka (2018) suggest, "*sustainability is surely a wide concept and some researchers agree on the idea that there is a lack of consensus on what sustainability means and how to effectively integrate it on a production system*". Regarding sustainable performance, two trends emerge. First, the predominantly economic approach to sustainable performance, evaluates the ability of a company to prevail in the long-term and maintain a sustained growth (Azim Azuan et al., 2020; Kowang et al., 2016; Nordin and Belal, 2017). Instead, the second approach follows the TBL perspective, and considers sustainable performance as a balance between performance in operational/economic, environmental, and social aspects (Raj et al., 2017; Rodrigues et al., 2016; Slaper and Hall, 2011).

Either approach has practical complications that make sustainable performance benchmarking between companies a complicated task. Long-term measurements can be useful for companies with a solid indicators base and the discipline to ensure comparability and timely follow-up (Dočekalová and Kocmanová, 2016). However, long-term assessment in academic research requires longitudinal analysis (Danese et al., 2018) that are time and resource consuming , and are usually limited by the number of companies or processes to be studied (Hernández Sampieri et al., 2010). In fact, according to Jasti and Kodali (2014), less than 4% of empirical research articles on LM published since 1990 employ longitudinal research methods.

A growing alternative to provide some level of international and inter-sectorial comparability of sustainable performance of organizations is that of voluntary reporting initiatives. It urges companies to report their adherence to a series of indicators that are commonly available, and therefore, a "Sustainability Index" can be calculated based on the number of items (i.e. governance, accounting, environmental, and social initiatives) that the company actually have. Some of the best-known reporting frameworks are presented in Table 16. However, difficulties related to these sources have also been pointed-out (Labuschagne et al., 2005).

Table 16. Sustainability reporting frameworks

Institution	Reference document	Description
Global Reporting Initiative (GRI)	G4 Sustainability reporting guidelines	Framework consisting of economic, environmental, social, and governance indicators
International Integrated Reporting Council	The international reporting framework	Framework for corporate sustainability and value reporting
United Nations Conference on Trade and Development	Guidance on corporate responsibility indicators in annual reports	Environmental, social, and governance indicators overview
United Nations Sustainable Development Goals (SDG)	Sustainable development goals	A call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet
CFA Institute	Environmental, social and governance factors at listed companies: a manual for investors	Environmental, social, and governance factors to be considered in company investments
Society of Investment Professionals in Germany	Key performance indicators (KPI) for extra-/non-financial reporting	Non-financial reporting framework
European Academy of Business in Society	Corporate responsibility, market valuation and measuring the financial and non-financial performance of the firm	Non-financial and environmental, social, and governance drivers of market value
Kynder Lydenberg and Domini (KLD)	MSCI ESG Sustainable Impact Metrics	Largest longitudinal database. Rating of companies based on environmental, social, and governance performance
International Standards Organization (ISO)	ISO 9001; ISO 14001; ISO 26000	Quality, environmental, and social, integrated management systems and standards

Adapted from: (Agudo Valiente et al., 2012; Barnett and Salomon, 2012; Dočekalová and Kocmanová, 2016; Hasan et al., 2016; Souza et al., 2018; Wang, Lu, et al., 2016)

Many of the indicators used in GRI and KLD index are either qualitative or binary (present, not present), which makes them difficult to compare or evaluate their evolution (Hasan et al., 2016; Sutherland et al., 2016). Moreover, metrics in GRI reports are extensive, which makes it difficult to analyze their content (Chen et al., 2015), and which makes them unlikely to be all relevant in all organizations (Jonkutė and Staniškis, 2016). In turn, ISO 14000, and ISO 26000 provides environmental and social guidelines, which, while helpful, remain subject to the interpretation of each company, and are not necessarily translated into assessment tools (Hutchins and Sutherland, 2008; Jonkutė and Staniškis, 2016; Sutherland et al., 2016). Another important concern related to KLD reports and many other reporting indexes is that they are often too general or measure performance on a higher level (community welfare, social development, child mortality, education, etc.), providing little support to a company which attempts to improve its sustainable performance in their day to day operation (Dočekalová, 2013; Hasan et al., 2016; Jacobs et al., 2016; Sutherland et al., 2016).

Recently, one of the most covered trends in sustainability relates to the United Nations Sustainable Development Goals (SDGs). It consists of a set of seventeen goals (represented in Figure 22) that should be pursued globally by both governments and profit and non-profit organizations (Goti et al., 2018). In order to achieve a "*better and more sustainable future for all*", all goals should be reached by 2030 (United Nations, 2018). Nevertheless, at manufacturing (and industrial) level, this goals framework becomes too abstract for managers to implement and follow, as it is the case with other reporting frameworks (Dočekalová and Kocmanová, 2016; Fleacă et al., 2018; Jacobs et al., 2016; Sutherland et al., 2016). For example, production managers (and even general managers) in most manufacturing companies might find difficult to build a direct and concrete set of indicators to follow goals like “zero hunger”, “life bellow water”, and “peace justice and strong institutions”, and develop actions to pursue them. In fact, a recent literature review performed by Bittencourt et al. (2019) concluded that lean practices contribute directly to only three of the seventeen goals (Goal 8, Goal 9, and Goal 12).

Figure 22. UN Sustainable development goals. *Source: (United Nations, 2018)*

In light of the issues presented with current reporting frameworks, and the fact that the spread of those frameworks along Colombian metalworking industry (which is the object of this research) is still scarce[6] and subject to many challenges; the proposed survey will follow the TBL approach to sustainability assessment. The TBL approach is easier to operationalize at a manufacturing and business level (Gong et al., 2018), and a significant amount of indicators for each TBL pillar can be found in literature (Abdul-Rashid et al., 2017).

Sustainable performance will be considered as a second order latent construct, which, according to the TBL approach, reflects in three first order latent constructs: operational performance, environmental performance, and social performance. Finally, each one of the TBL performance constructs reflects on a series of indicators drawn from current literature, which are presented in Table 17 along with their corresponding Spanish translation. In addition, the sustainable performance measurement model is graphically represented in Figure 23.

The set of each TBL pillar indicators employed are in line with Shahbazi et al. (2018) most cited characteristics for sustainability indicators: quantifiable and measurable, comparable (between companies, and over time), easy to understand and interpret, concise and easily communicated, limited in number, linked to a defined goal and action oriented, supports decision-making, and provides sufficient information to raise awareness. Said characteristics are also deemed important by other authors such as (Ciannella and Morioka, 2018; Dočekalová and Kocmanová, 2016; Zhang et al., 2017).

[6] According to GRI Sustainability disclosure database, by 2017 only 282 Colombian companies were using GRI reporting guidelines, and only 2 of them fell in the “Metal Products” category.
Source: https://database.globalreporting.org/search/ retrieved on June 2019.

• **Operational performance:** the vast majority of lean manufacturing empirical research relates to the effects of LM on operational performance (Henao et al., 2019; Negrão et al., 2017). Therefore, there is (to an acceptable degree) some consensus of variables that are reliably indicators of operational performance. However, it is important to mention that (as exposed in Section 1.5.1), while operational performance usually has some level of correlation with economic and business performance, the latter is also affected by external variables such as market and financial performance (Abdul-Rashid et al., 2017; Busse, 2016; Büyüközkan et al., 2015).

In consequence, as the independent variable for this research is related exclusively to the manufacturing strategy (i.e. implementation of LM), its effects are directly reflected at operational level (Negrão et al., 2017), hence, the dependent variable for this branch of TBL performance will be considered as operational performance. This approach is in line with most management empirical research involving sustainable performance, a fact evidenced by Gong et al. (2018) literature review: "*the triple-bottom line perspective the authors focused on is at the operational level (company level) performance metrics instead of the country-level macroeconomic sustainable performance metrics*".

Many studies have provided evidence that cost, quality, delivery, lead time, inventory levels, and flexibility can be strong indicators of operational performance (Arcidiacono et al., 2016; Avella and Vázquez-Bustelo, 2010; Ghalehkhondabi, 2017; Ishaq Bhatti et al., 2014). Those six performance measures are present in almost all LM empirical research that assess some level of operational performance (as evidenced by Table 17), since it is widely supported that LM principles and practices are predominantly aimed to directly improve them (Belekoukias et al., 2014; Martínez León and Calvo-Amodio, 2017; Thanki et al., 2016).

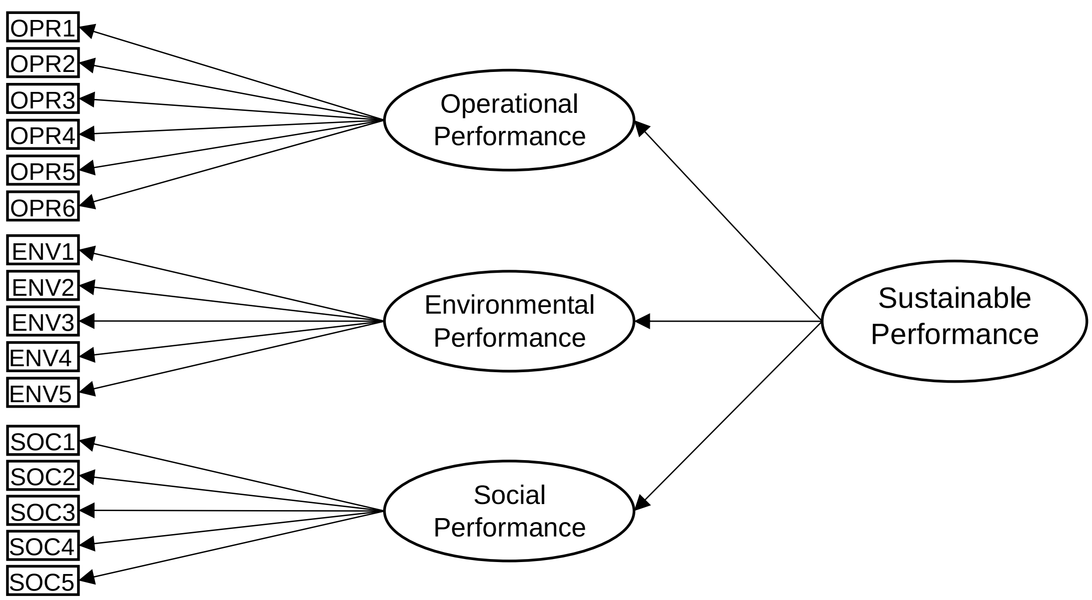

Figure 23. Sustainable performance construct

• **Environmental performance:** form an operations management viewpoint, environmental performance can be approached from two perspectives: internal effects and external effects. Internal effects consider environmental impacts derived from production and manufacturing processes, while the external effects consider those impacts generated upstream and downstream on the supply chain (Campos et al., 2015; Maceno et al., 2018). According to Younis et al. (2016), environmental performance can be defined as the ability of a company to reduce those impacts, with the most prominent being air emissions, effluent waste and solid wastes, consumption of hazardous and toxic material, and the frequency of environmental accidents.

For the purpose of this research, the survey instrument will focus on internal effects. The main reason for this approach, relies in the fact that Colombian metalworking industry is mainly composed by SMEs[7] which often lack the capacity and resources to make an extensive follow up of environmental impacts in their entire value chain. Furthermore, being a developing country, a large quantity of SMEs focus mainly on economic survival (Sajan et al., 2017; Shrafat and Ismail, 2019), rather than their impacts on the other two pillars of TBL (Caiado et al., 2017; Hutchins and Sutherland, 2008). This is a common scenario for other developing countries, with data from Labuschagne et al. (2005) showing that more than 90% of a sample of South African SMEs considered financial health and economic performance highly relevant, and prioritize it compared to environmental and social performance.

While the application of LM practices can have contrasting effects on different stages of the value chain (like supply, production, or distribution) (Bergenwall et al., 2012; Martínez León and Calvo-Amodio, 2017), those effects are most likely to be evidenced at manufacturing level (Nujoom et al., 2017; Verrier et al., 2016), in easily followed internal indicators related to waste and emissions generation, energy efficiency, and environmental compliance (Dieste et al., 2019; Garza-Reyes et al., 2018; Resta et al., 2017).

• **Social performance:** when dealing with social performance, measurement challenges can be observed even in advanced economies (Distelhorst et al., 2017), furthermore in developing countries. Those challenges are exacerbated by the need to measure aspects associated with emotions, motives, believes, feelings and empowerment, among others (Agudo Valiente et al., 2012; Bernhardt and Pollak, 2016; Sutherland et al., 2016; Wang, Hsu, et al., 2016).

Manufacturing companies are being pressured to introduce SP indicators, in order to assess the social outcomes operations (Dočekalová, 2013; Zhang et al., 2017). However, the most disclosed issue with SP assessment is related to the scarcity of research in SP metrics (Bernhardt and Pollak, 2016; Boukherroub et al., 2013; Hutchins and Sutherland, 2008), particularly in the manufacturing industry, as well as the need for unified and well-defined measures, metrics, or indicators (MMI) (Sutherland et al., 2016; Zhang et al., 2017) which are sufficiently accepted on an international level (Chen et al., 2015).

This research will consider internal social performance metrics, which means that the performance impact is reflected directly on the company and its employees. Internal indicators can relate to two categories: a) labor practices and work conditions; b) worker welfare and development. Labor practices and work conditions are metrics directly related to the workforce (Chen et al., 2015; Siebert et al., 2018) and, according to Dočekalová (2013), they are considered to be the core of company social performance. It gathers most of the basic aspects with which the company must comply, generally as a legal requirement. In turn, worker welfare and development goes beyond legal

[7] According to data from “Encuesta anual manufacturera - 2017” 599 (94%) companies in metalworking sector were classified as SMEs, from a total of 640 companies in that sector.
Source: https://www.dane.gov.co/index.php/estadisticas-por-tema/industria/encuesta-anual-manufacturera-enam retrieved on June 2019.

requirements, and comprises indicators that measure the company's effort to protect its employees and improve their quality of life (Ishaq Bhatti et al., 2014). Internal metrics are more likely to be implemented and monitored, as they are mostly quantitative (Chen et al., 2015), data sources are inside the company, and can be compared against well-known local and international standards.

Table 17. Sustainable performance observed variables

TBL	Code	Indicator (English)	Indicator (Spanish)	References
Operational	OPR1	Cost	Costo	[1,2,3,4,6,7,10,11,13,15,16,17, 19,20,21,23,25,26,31,32]
	OPR2	Quality	Calidad	[1,2,3,4 ,5,6,7,11,15,16, 17, 19,20,21,26,31,32]
	OPR3	Lot size flexibility	Flexibilidad en tamaño de lote	[1,2,3,7,15,16,17,19,20,31]
	OPR4	Production lead-time	Tiempo de producción	[2,3,4,7,11,15,16,17,19,20,21,25,32]
	OPR5	Cycle time (manufacturing cadence)	Tiempo de ciclo (cadencia de producción)	[3,6,11,15,20,25,26]
	OPR6	Work in process inventory	Inventarios en proceso	[2,3,6,11,16,19, 20,21,26]
Environmental	ENV1	Use of hazardous materials in production process	Uso de sustancias peligrosas en procesos productivos	[1,4,5,6,8,9,11,12,22,23,28,30,32]
	ENV2	Solid-waste generation	Generación de residuos sólidos	[1,4,5,6,8,10,11,12,13,14, 18,21,22,24,28,32]
	ENV3	Green-house gas emissions	Emisión de gases de efecto invernadero	[1,5,6,8,10,11,12,13,14, 18,21,22,23,24,28,30,32]
	ENV4	Energy efficiency in production processes	Eficiencia energética de los procesos productivos	[1,4,5,6,8,10,11,12, 13,14,23,24,28,30]
	ENV5	Environmental regulation compliance	Cumplimiento a regulaciones ambientales	[1,5,6,9,10,14,18,24,32]
Social	SOC1	Wages and economic compensation	Salarios y compensación económica	[9,21,27,29]
	SOC2	New direct and formal workplaces creation	Generación de nuevos empleos formales y directos	[13,15,21,22,27,29]
	SOC3	Employee turnover rate	Tasa de rotación del personal	[10,14,15,22,27,28,31]
	SOC4	Accident rate	Tasa de accidentalidad	[1,6,10,13,14,15,18,21, 22,23,27,28,29,32]
	SOC5	Employee satisfaction and motivation	Satisfacción y motivación del personal	[1,5,6,15,18,19,21,23,31,32]
[1]Abdul-Rashid et al., 2017; [2]Avella and Vázquez-Bustelo, 2010; [3]Belekoukias et al., 2014; [4]Bergmiller and Mccright, 2009; [5]Caiado et al., 2017; [6]Cherrafi et al., 2016; [7]Dal Pont et al., 2008; [8]Dieste et al., 2019; [9]Distelhorst et al., 2017; [10]Dočekalová and Kocmanová, 2016; [11]Farias et al., 2019; [12]Garza-Reyes et al., 2018; [13]Gong et al., 2018; [14]Ioannou and Serafeim, 2017; [15]Ishaq Bhatti et al., 2014; [16]Khanchanapong et al., 2014; [17]Machuca et al., 2011; [18]Martínez León and Calvo-Amodio, 2017; [19]Negrão et al., 2017; [20]Pakdil and Leonard, 2014; [21]Resta et al., 2017; [22]Rodrigues et al., 2016; [23]Sajan et al., 2017; [24]Sarache-Castro et al., 2015; [25]Shah and Ward, 2003; [26]Shrafat and Ismail, 2019; [27]Siebert et al., 2018; [28]Stindt, 2017; [29]Sutherland et al., 2016; [30]Verrier et al., 2016; [31]Vivares-Vergara et al., 2016; [32]Younis et al., 2016				

2.5. Reliability and validity tests

In spite of using already tested variables for measuring lean manufacturing implementation level and sustainable performance, it is important to make a proper validation of the measurement instrument (i.e. the survey), as part of some essential considerations that have to be made while adapting indicators and scales used for different studies or employed in different contexts (Abolhassani et al., 2016; Nawanir et al., 2018; Vargas-Halabí et al., 2017). Among said considerations are:

1. Context factors: since the proper and successful implementation of lean manufacturing varies from one country to another, and also in each business sector (Henao et al., 2019; Nordin and Belal, 2017), the indicators for measuring it also varies from one context to other (Tortorella et al., 2017). It has been widely documented that some practices that can give promising results in some industries, fail to perform equally in others (Negrão et al., 2017). Therefore, not necessarily all indicators that had been already employed in one sector all relevant to other (Machuca et al., 2011). As the research object of the present study focus on metalworking industries, and none of

the previously applied questionnaires found in literature, were directly conceived for this sector, the relevancy of the chosen indicators has to be validated within the study object (Moyano-Fuentes et al., 2019; Prasad et al., 2016).

2. Language factors: all reviewed lean manufacturing and performance questionnaires from literature were presented in English. However, many of the original studies were applied in non-English speaking countries. In the case of the present research, since the data collection instrument is to be applied in a sample of Colombian companies, it has to be properly translated to Spanish (Vargas-Halabí et al., 2017). This translation (and in some cases, double translation, from the original language of the study, to the English publication, and finally, to the Spanish survey), can result in a loss of meaning and content validity (i.e. the ability to properly measure the intended construct) if not properly conducted and validated (Bortolotti, Boscari, et al., 2015; Pérez-López et al., 2019; Shrafat and Ismail, 2019). Also, in industrial contexts, some terminology is often adapted in particular sectors which means that the literal translation of technical terms of lean manufacturing practices or performance related indicators is not necessarily understood as the same in a different country or industrial sector (Hyrkäs et al., 2003; Ketokivi and Schroeder, 2004; Machuca et al., 2011). Finally, some terminology (especially regarding lean manufacturing practices) is often widespread in its original language, as it is the case of *Kaizen* (almost universally understood as a continuous improvement practice), or *SMED* (single minute exchange of dies), which are terms commonly used in Spanish-speaking companies even by non-English-speaking persons (Arrieta et al., 2011; González Gaitán et al., 2018; León et al., 2017).

The above mentioned factors, along with different methodological issues (Creswell, 2014), make for a necessary validation of the data collection instrument. This pre-testing prevents from distributing the instrument to a large-scale sample, only to find later that the collected data might not be completely useful (Nawanir et al., 2018). Therefore, it becomes important to validate different aspects of the survey, its structure, and ultimately, its questions, to guarantee:

- Content validity: content validity relates to the ability of the selected items to properly measure the domain they are intended to represent (Creswell, 2014). Since this is a criteria-based validation (it is not possible to produce a numerical validation of content) (Moyano-Fuentes et al., 2019), the most commonly employed method is an expert validation of the items derived from an extensive literature review (Abolhassani et al., 2016; Shrafat and Ismail, 2019), both from academics and practitioners with extensive knowledge of the field of study (Chavez et al., 2015; Tortorella et al., 2017; Vivares-Vergara et al., 2016).

- Predictive validity: predictive validity means that the survey items can effectively predict another variable (Creswell, 2014). This is specially necessary when dealing with correlational studies (Bagozzi and Yi, 2012), but it is important to consider that it only applies (in SEM) to reflective constructs (Davcik, 2014), as it is the case of this research.

- Convergent validity: since the survey items are intended to represent different constructs it becomes important that the measures of each individual item converge together, meaning that they share a notable percentage of the construct variance (Garza-Reyes et al., 2018; Katiyar et al., 2018; Nawanir et al., 2018). In simpler words, a high convergent validity means that the results of each item of a single construct point in the same direction.

- Reliability: reliability gives a measure of how the survey items (i.e. questions) of a single construct are effectively measuring the same dimension (Bagozzi and Yi, 2012). Convergent validity, unidimensionality (Khanchanapong et al., 2014) (the "spread" of the measures being predominantly oriented along a single axis or dimension), and reliability constitute measures of internal consistency (Moyano-Fuentes et al., 2019), which means that are related to each individual construct and their items (Davcik, 2014), regardless of the interactions between different constructs.

- Discriminant validity: constructs are intended to represent a conceptual dimension (in this case, the level of lean manufacturing implementation, and sustainable performance) through a series of measures (items) that reflect that particular concept. Since each construct is intended to measure a different dimension (i.e. a different variable) it is important that they indeed are sufficiently different from each other (Khanchanapong et al., 2014; Moyano-Fuentes et al., 2019). In other words, discriminant validity is important to ensure that two different constructs are not measuring the same dimension or concept (Awan, 2019; Davcik, 2014).

The survey validation process follows a methodology adapted from similar research in the same field, that it is often used by authors conducting SEM studies from data collected through survey questionnaires, such as Abolhassani et al. (2016), Garza-Reyes et al. (2018) and Katiyar et al. (2018). The different steps represented in Figure 240, are sub-steps from the fifth and sixth stages of the general research methodology presented in Figure 17.

The first validation step was approached through an expert's assessment, which evaluates the sufficiency, understandability, and relevancy of each question, as well as the constructs that are intended to be represented by the observed variables. The results of the assessment as well as the improvements to the survey derived from the experts' suggestions are presented in Section 3.2.1. Then, an empirical validation was performed through a case study. Although the experts consulted in the first step had both academic and practice backgrounds, the case study allows to close several gaps that can arise between the theory and the practical implementation of lean practices in the studied object. In addition, the qualitative component of the case study will be a valuable asset for the interpretations of the results from the quantitative phase of the research. Therefore, a detailed description of the case study methodology and objectives is presented in Section 2.5.1 and the main results are gathered in Section 3.2.2.

Finally, reliability and validity tests were performed using a two-stage approach. The first stage was performed at a general scale using the preliminary survey results gathered through a reduced non-random sample (pilot study). After obtaining adequate reliability and validity results from the pilot sample, the survey was distributed to the complete sample of companies using a random-sampling approach, and the complete set of specific reliability and validity tests were applied to the final dataset. The results for the pilot test are presented in Section 3.2.3, and the final reliability and validity tests results are covered in Section 3.5.

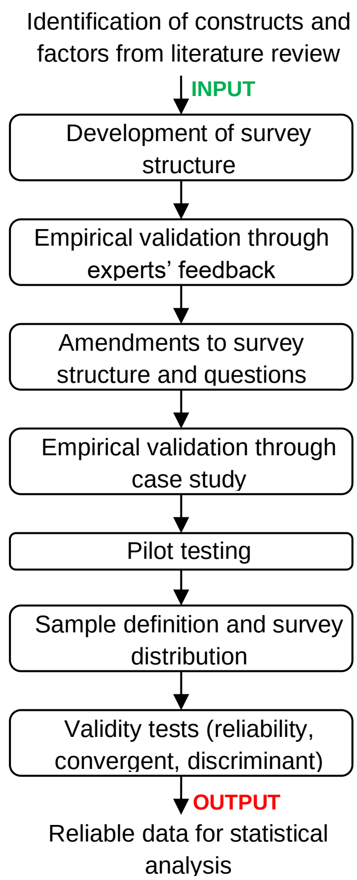

Figure 24. Survey design and validation methodology. *Based on: (Abolhassani et al., 2016; Abu et al., 2019; Ali et al., 2020; Garza-Reyes et al., 2018; Katiyar et al., 2018; Tsang et al., 2017)*

2.5.1. Case Study

Section 2.2.1 details the methodological approach of the present research, along with the general considerations and reasoning behind the inclusion of a case study as part of the qualitative approach of some of the research steps. Mainly, many authors have reported gaps between theory and practical implementation of LM, and some of them have found those gaps to be highly dependent on cultural context and industry sector (Chavez et al., 2015; Čiarnienė and Vienažindienė, 2014; Henao et al., 2019; Shah and Ward, 2003). This, claim is also supported by the contingency theory (specifically applied in LM) which specify that there is no universal path for a successful LM implementation (Danese et al., 2018; Sunder and Prashar, 2020) and no single manufacturing strategy will present the same results in all companies. Instead, there is some evidence suggesting that the success of LM programs depends (at least partially) in the way that companies manage to adapt lean practices to their own production systems and organizational culture (Netland, 2016).

Many of the critical success factor (CSF) for lean implementation that have been identified in literature by authors such as Alhuraish et al. (2017), Bortolotti, Boscari, et al. (2015), Netland (2016) and Sunder and Prashar (2020), converge in the Colombian metalworking industry, creating several gaps that companies face while adopting LM. First, as presented in Chapter 1, most lean principles and the lean production system can trace their origins to Japan, which presents a clear cultural gap with Latin-American countries. Second, most of lean practices were introduced to Colombian industries trough the automotive supply chain (as stated in Section 1.7), which creates a process gap with companies from other sectors. Third, as it is well documented, a successful lean program requires a long-term orientation an high management commitment (Čiarnienė and Vienažindienė, 2014; Negrão et al., 2017), which is especially difficult for small companies struggling to survive in a day-to-day basis, thus, creating a company size gap, especially since over 80% of Colombian metalworking companies classify as SMEs (DANE, 2019). Finally, as the SLR presented in Section 1.7 evidences, specialized literature regarding lean manufacturing implementation in Colombian industries is scarce, which creates a context and scientific gap, as practitioners are forced to adapt practices and implementation methods originally developed for different countries.

All these aspects could result troubling when dealing with the interpretation of the research results gathered trough the developed data collection instrument because the theoretical backgrounds (critical to make a proper interpretation of empirical research results (Kaplan and Duchon, 1988)) could present the above-mentioned gaps. In this way, the conducted case study helps to bridge some of those gaps and strengthen the theoretical basis and practical implications that will come in light of the statistical results presented in subsequent sections, improving the expected impact of the present research, in both practical and scientific theory development aspects (Verrier et al., 2014).

A case study is a commonly employed practice in OM (an social sciences in general) research, where a particular phenomenon is deeply studied on a single (or multiple) object in order to support the existence of a given research problem, test hypotheses, develop theories, or provide evidence that a given theoretical proposition is evidenced in reality (Hernández Sampieri et al., 2010). Case studies can be experimental (when the researcher has influence on the studied variables) or non-experimental (when the researcher only “observes” the phenomenon), with the latter case being employed for this research. Case studies generally combine quantitative and qualitative techniques (Creswell, 2014), which render them relevant where there is scarcity of metrics and theoretical definitions for subsequent empirical studies (Bergenwall et al., 2012; Shahbazi et al., 2018).

A properly conducted case study should contribute to establishing a satisfactory level of reliability and validity of the studied constructs or variables (Nawanir et al., 2018; Nordin and Belal, 2017). In the case of the present research, metrics and definitions for the involved variables and constructs are readily available from the state-of-the-art literature reviewed in the theoretical framework. However, it is important to notice that the extension to said metrics and definitions to the studied object (Colombian metalworking industry) remains scarce, therefore the relevance of including the case study stage in the methodological set-up.

The adopted methodology for the case study follows an approach commonly used in OM research (Bergenwall et al., 2012; Goti et al., 2018; Nordin and Belal, 2017; Sadiq et al., 2021; Verrier et al., 2014), when case studies are performed for similar purposes as this one. It is important to notice that the present research is not based on a case study, but in a survey data collection, therefore, the proposed case study represent just a part of the methodological approach for specific purposes that does not include the hypothesis testing. In this sense, the case study methodology employed lacks the depth (and does not necessary covers all the steps) that are needed when a case study is the “core” of the data gathering instrument of a research, and its data is used for hypothesis testing. The proposed methodology covers two main stages as shown in Figure 25, the first one, focusing on the theoretical backgrounds and, the second one, focusing on the empirical, data gathering part.

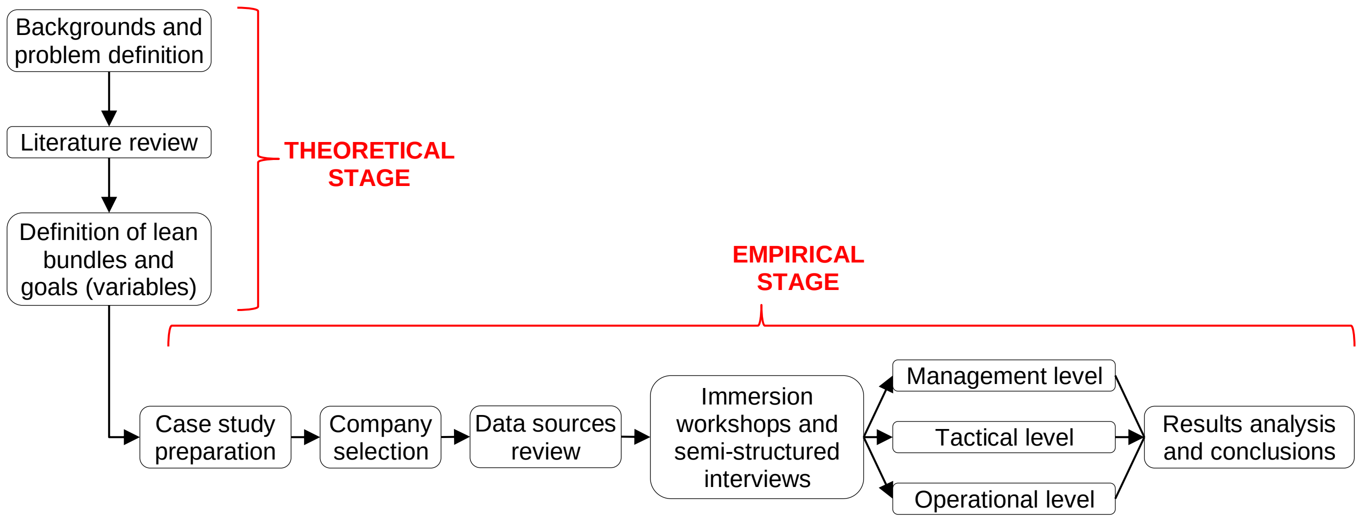

Figure 25. Case study methodology

The three steps comprising the theoretical stage were already developed in Chapter 1 and Chapter 2, arriving to the lean and sustainability measurement items described in Table 15 and Table 17. The empirical stage followed through the steps shown in Figure 25 with a 5WH approach, which is a common practice in many lean problem-solving methodologies (Garza-Reyes et al., 2018; Zhang et al., 2017). Since one of the main goals of the case study centers on the scale (i.e. the survey items) validation, those lean goals are taken as the base-point of the 5WH shown in Table 18. The 5W and 1H questions were asked about each one of the LM items, following a procedure similar to that proposed by Creswell (2014). The question rounds were divided into three different focus groups with different objectives, and a slightly different approach to the questions.

Table 18. 5WH case study approach

Which?	Which lean practices or tools have been implemented to pursue the described lean goal?
Why?	Why did the company decided to apply (or not) that given practice?
Who?	Who led the implementation of said practice in the company?
How?	How was the practice implemented? Which theoretical referents were used for implementation and which adaptations were necessary?
When?	When did the company started that practice implementation, and how much time was necessary to start perceiving results?
What?	What KPIs (operational, environmental, social) did the company managed to impact through that practice implementation?

Other sources of information reviewed included the company product catalog and website (which are not disclosed due to confidentiality). The company also granted the researcher access to performance reports and indicators, as well as some of their records related to the implementation of some lean practices, meeting minutes relating lean training, the procedures for their human resource management, standardized training, planning, supply, and quality processes, and their annual sustainability report, that the company has been presenting in the annual shareholders meeting since 2015. Data gathered from said sources, as well as that from the interviews and workshops was employed to validate the data collection instrument, as well as an input for the interpretation of the quantitative results (Section 4.1).

The main results from the case study are presented in Section 3.2.2. However, the qualitative results from the case study represent also an important base for the interpretation of the results of Section 3.6 (the results of the hypotheses testing), and the further discussion and interpretation of the obtained results, which are presented in Chapter 4, therefore, other relevant results obtained from the case study are presented through Chapter 3 and Chapter 4 where applicable.

2.6. Partial Conclusions

Empirical research has been widely employed in cause-effect relationship studies in operations management, including lean manufacturing. The scale of the relationships, the quantity of data, and the quantity of variables analyzed have grown considerably thanks to the introduction of computational-based statistical methods and tools such as structural equation modelling.

The proposed research design follows an empirical-analytical approach, enclosed in a mixed (i.e. qualitative and quantitative) methodology approached from a *critical realism* ontological position, and a *post-positivist* epistemological position. It profits from the advances in statistical data processing methods and previous experience to deal with the effects of lean manufacturing (independent variable) in sustainable performance (dependent variable), approached from a triple bottom-line perspective. Two structural equation models are proposed to test the two main hypotheses derived from the knowledge gaps found in state-of-the-art literature.

The first hypothesis suggests a cumulative approach to sustainable performance, in which operational performance improvement serves the base for environmental performance gains, and finally, the first two sets the grounds for social performance enhancement. The second hypothesis proposes a trade-offs approach, in which, improvements on one pillar of triple bottom-line performance (i.e. operational, social, or environmental), come at the detriment of one (or both) of the other two.

Following the structural equation model approach, two measurement models are presented, one for each of the main variables. Lean manufacturing is presented as a second order latent variable, reflected in six first order constructs (HRM, management, planning and processes, supply, quality, and technology), which in turn reflect in 23 observed variables. Sustainable performance is measured following the triple bottom-line approach; hence it is also considered as second order latent variable, reflected in three first order constructs (operational performance, environmental performance, and social performance). Those first order constructs reflect on a total of 16 observed variables which, like the ones used for lean manufacturing, were derived from current academic literature.

Finally, it can be concluded that, the proposed research design follows a known path of structural equation modelling based empirical research, towards an unknown horizon regarding the effects of lean manufacturing in sustainable performance.

CHAPTER 3. RESULTS

3.1. Introduction

The present research follows an empirical, survey-based, approach to data collection, with a subsequent statistical analysis for testing the proposed hypotheses. In this context, some steps have to be followed to ensure a satisfactory outcome from a methodological point of view, and give the obtained results reliability, validity, and conclusive characteristics.

The data collection instrument (i.e. the survey) validation is essential to ensure that the variables being measured are those relevant to the phenomenon that is being studied, and the questions being asked are appropriate to assess said variables. In this case, the survey validation was achieved using an expert's assessment method, on which eleven experts (some of them world known) on the fields of lean manufacturing and sustainability, with backgrounds on academic, research and industrial contexts assessed the variables, constructs, measurement scales, and questions, to ensure their validity, understandability, and sufficiency.

To help close cultural and language gaps that can exist between the theoretical frameworks derived from the state-of-the-art literature, and the practical context of the studied object (the Colombian metalworking industry), a case study was performed as a second step of the validation. A Colombian metalworking company with a considerable level of lean manufacturing implementation was analyzed mostly with qualitative research methods to evaluated if the identified variables for lean implementation level and sustainable performance assessment, were indeed present and relevant in the context of the studied object. The study also allowed to gather valuable insights into the dynamics of lean manufacturing implementation in the context of the Colombian metalworking industry, that resulted helpful for the interpretation of the obtained results later on.

Finally, a pilot test was conducted on a reduced sample of companies, with the aim of identifying possible problems both with the instrument, its interpretation by the respondents, or the underlying constructs structure of the data. The final sample of companies was obtained from a census of Colombian metalworking companies retrieved from the chambers of commerce of the main industrial centers of the country, resulting on a final sample of 133 companies, which represents a response rate of 16%, adequate enough in accordance to accepted research standards in the same field.

It is important to notice that most of the data collection was performed during the COVID-19 pandemic that mostly affected Colombia from April to September 2020. The health, social, and economic turmoil that resulted worldwide must likely affected the gathered information. It is however difficult to quantify the exact effect of the pandemic in the studied phenomenon, but with the methodological rigor followed through the data collection and data analysis it can be ensured that the results represent a clear picture of how the involved variables are interacting.

The obtained data was analyzed using structural equation modeling (SEM) methods. Prior to testing the proposed hypothesis, the measurement model was validated using principal components analysis and confirmatory factor analysis, to test if the underlying data structure was appropriately related to the theoretical constructs that it was intended to represent. After the empirical validation of the measurement models, several structural models were proposed (and empirically tested) to evaluate different cause effect relationships between the independent (lean manufacturing implementation level) and dependent (sustainable performance) variables.

The results supported hypothesis 1, meaning that cumulative gains on performance dimensions can be expected when implementing lean. Said gains follow a “sand-cone” sequence that has operational performance at the base, followed by environmental performance, and social performance on top. On the other hand, only partial support for hypothesis 2 was found. Partial trade-offs models were tested, with results suggesting that while implementing lean with simultaneous performance improvement expectations on all TBL dimensions, trade-offs are likely to manifest between operational and environmental pillars, with the social pillar. The latter, being negatively affected by improvements on the other two.

The present chapter follows all the methodological considerations for a proper data collecting instrument validation, and statistical processing of the gathered data to obtain meaningful and reliable results. Therefore, it is structured as follows: Section 3.2 presents the data collection instrument validation and the case study performed, Section 3.3 describes the selected sample and data collection process, while Section 3.4 shows the descriptive results obtained from the gathered data. The measurement models validation and relevant validity and reliability tests are presented in Section 3.5, and finally, Section 3.6 present the different structural equations models proposed, including the hypotheses testing.

3.2. Data collection instrument validation

To collect the relevant data of both independent (lean manufacturing) and dependent (sustainable performance) indicators, a survey was designed using existing items for both variables, derived from state-of-the-art literature. The selection and development of all measuring items was presented in Section 2.4. The validation process follows the methodology presented in Section 2.5 (Figure 24), and the results of the validation process, along with the required adjustments in the data collection instrument, and the final survey, are presented in the following sub-sections.

3.2.1. Experts’ assessment

The LM and Sustainable performance variables to be assessed (presented in Table 15 and Table 17) were developed into a first version of the questionnaire. Since the items selected to measure each one of the constructs were extracted from the state of the art after a careful literature review, a high level of validity and reliability for each items and construct can be expected (Moyano-Fuentes et al., 2019; Wan Ahmad et al., 2020). In other words, the questions for each construct were selected based on questions from surveys found in literature which had undergone previous validation tests (Bortolotti, Boscari, et al., 2015).

Nevertheless, as previously exposed, neither of the previous questionnaires used as reference was specifically developed for a causational analysis of the two main variables of this research, nor to be applied in the Colombian metalworking industry. Furthermore, since the questions had to be translated to Spanish, those matters could create reliability issues that need to be addressed conducting the necessary tests (Nawanir et al., 2018; Pérez-López et al., 2019).

An expert validation of the survey instrument was performed, following a common path in OM and LM empiric research (Awan, 2019; Marodin et al., 2019; Nawanir et al., 2018; Tortorella et al., 2017). To expedite the validation process, a purpose-developed Google Forms survey was employed, which comprised three main focuses. First, to validate if the proposed scales for each variable were acceptable (Ali et al., 2020; Dey et al., 2020). Second, to verify the understandability and validity of each question (Escobar and Cuervo, 2008; Nawanir et al., 2018); and third, to confirm that the proposed questions were deemed sufficient to properly measure each construct (Sajan et al., 2017; Shrafat and Ismail, 2019). The developed instrument can be found on Appendix A.

The validation instrument presented the survey questions in the same structure and order of the data collection instrument, however, it asked the respondent to assess the validity and understandability of each question, and the sufficiency of questions for each construct, instead of asking for an assessment of the LM implementation or performance level as in the final questionnaire. The suitability of the measurement scales and understandability of each item was evaluated through a closed binary (i.e. yes/no) question, while the validity was assessed using a 5-point Likert scale (1: non-relevant, 5: highly relevant). Finally, an open answer question included at the end of each section asked about redundant or missing items, and additional comments and suggestions to enhance the final data collection instrument. The las part of the validation questionnaire recovered demographical data from the experts.

A panel of experts was selected comprised with both academics and practitioners to conduct the instrument validation. Experts were contacted by telephone, WhatsApp, Research Gate, and e-mail, as suggested by Abu et al. (2019). Upon receiving confirmation of their willingness to participate, an official e-mail presenting the research project was sent, along with the instructions, and a link to the Google Forms on-line validation instrument. The invitation letter and instructions can be found in Appendix B (some information was omitted for confidentiality purposes). In 40% of the cases, the methodology used was a guided face-to-face survey, where the experts received the validation process instructions and questions were asked directly by the researcher and filled into the purpose-developed instrument. This allowed the researcher to dig an expand the expert thoughts and perceptions around the different items, as well as gathering valuable suggestions for the final survey as well as for the overall research methodology. In other 30% of the cases, the employed methodology was similar to the previously explained one, however, due to geographical restrictions the interviews were conducted virtually. In the remaining 30% of cases, the validation instrument was self-administered by the experts and the answers registered on-line.

A total of eleven experts participated in the review process, with more than 130 years of LM experience combined between them. The number of selected experts was deemed acceptable compared to similar research in the field (Awan, 2019; Marodin et al., 2019; Nawanir et al., 2018; Tortorella et al., 2017). The assessment was conducted using Colombian and Spanish experts in order to ensure that the review was performed in the same language of the final survey to be applied. This allows to identify not only technical LM and sustainable performance issues, like if the correct questions are being asked in order to properly represent the intended construct (Ali et al., 2020; Sodhi and Yatskovskaya, 2014), but also linguistic and cultural issues that might arise from concepts and perceptions about the measured variables differing on each country, therefore risking to alter the understandability of the question (Hyrkäs et al., 2003; MacKenzie and Podsakoff, 2012).

Nine of the experts had industry experience in LM and/or sustainability, while nine of them had academic and research backgrounds in both subjects. Industry related experts come from Colombian metalworking companies with well stablished LM programs, as well as sustainability practices. Academic and research experts were related to highly recognized Colombian universities and had extensive backgrounds in LM and sustainability topics. Two world-known Spanish researchers in LM and sustainability also participated in the assessment. All experts complied with the experience, availability and motivation, reputation and recognition, and impartiality criterions suggested by (Escobar and Cuervo, 2008). A detailed background of each expert is presented in Table 19. For the "LM expertise" and "Sustainability expertise" columns, the experts were asked to self-asses their level of expertise regarding Lean Manufacturing and sustainability, using a five-point Likert scale. The last column provides a hyperlink to each expert LinkedIn or ResearchGate profile, when available.

Table 19. Experts' backgrounds

Name	**Organization**	**Position**	**Experience[1]**			**Years of experience**	**LM expertise[2]**	**Sustainability expertise[3]**	**CV**
			P	**A**	**R**				
Fabio Gonzales	Metallan SAS	General Manager	X	X		30	5	4	
Daniel Vasquez Bustelo	Universidad de Oviedo	Professor	X	X	X	20	4	4	RG
Juan Gregorio Arrieta	Universidad EAFIT	Professor	X	X	X	15	4	2	in
Juliana Paola Arce	Impulso Colombia	Executive Director	X	X		14	5	3	in
Luis Carlos Botero	Induma SCA	R&D Manager	X	X	X	13	3	2	in
Elisa Maria Londoño	Herragro SA	Production Manager	X			11	4	3	
Jose Moyano Fuentes	Universidad de Jaen	Professor		X		10	5	3	in
Santiago Castaño	Incolmotos Yamaha	Quality Manager	X			7	4	4	in
Natalia Marulanda	Universidad Nacional	Assistant Professor		X	X	6	4	4	RG
Mariana Prieto	Renault Sofasa	Senior Buyer	X			5	3	3	in
Cesar Augusto Salazar	Sicolsa SA	Quality Manager	X		X	5	4	4	in

[1]P: professional; A: academic; R: research
[2, 3]5: high expertise; 1: basic expertise

The results of the expert's assessment were evaluated using a convergence criterion for each question (i.e. most experts opinion about an asked question point in the same direction), which is most commonly measured through a content validity index (CVI) (Polit et al., 2007; Wan Ahmad et al., 2020). Each item validity was assessed through a five-point Likert scale (a slight variation from Kim et al. (2020) and Polit et al. (2007) which proposed a four-point scale), and relevant items were considered with a value of 4 or 5 (relevant and highly relevant) to make for a more restrictive validity criteria. Table 20 represent the I-CVI (item content validity index) and S-CVI (scale content validity index), which is computed using the average of I-CVI, instead of the universal agreement method which is more restrictive and therefore more likely to produce divergent results when evaluating new instruments (Polit et al., 2007). The item coding used in the first column corresponds with the coding presented in Table 15 and Table 17.

The AVG column of Table 20 presents the average of all eleven experts validity grading for each item, which, if not as conclusive as the I-CVI, still gives a good idea of how relevant the item is for the scale, with five being highly relevant. As part of the survey validation instrument, each expert was asked about the understandability of each question, with two available choices: "the question is understandable" or "the question is confusing". The UND column, gives the understandability agreement index, which is the ratio of experts choosing "the question is understandable", therefore, a value of 1 means there is a complete consensus. Finally, the UVR column presents the understandability validity ratio, which is adapted from the CVR (content validity ratio) used by Wan Ahmad et al., (2020) to define consensus in dichotomous answers (i.e. "understandable" or "confusing").

Table 20. Item content validity and understandability

Scale	Item	AVG	I-CVI	S-CVI	UND	UVR
Lean Manufacturing Scale	HRM1	4,73	1,00	0,91	0,82	0,64
	HRM2	4,55	0,91		1,00	1,00
	HRM3	4,55	0,91		0,82	0,64
	HRM4	4,36	0,82		0,82	0,64
	MGM1	4,91	1,00		1,00	1,00
	MGM2	4,27	0,82		0,91	0,82
	MGM3	4,45	0,91		0,91	0,82
	PAP1	4,64	0,91		1,00	1,00
	PAP2	4,45	0,82		0,73	0,45
	PAP3	4,36	1,00		0,73	0,45
	PAP4	4,91	1,00		0,82	0,64
	SUP1	4,73	1,00		1,00	1,00
	SUP2	4,73	1,00		0,73	0,45
	SUP3	3,64	0,64		0,82	0,64
	SUP4	4,64	1,00		0,91	0,82
	QLT1	4,36	0,82		0,91	0,82
	QLT2	4,55	0,91		0,91	0,82
	QLT3	4,64	0,91		1,00	1,00
	QLT4	4,64	1,00		0,91	0,82
	TEC1	4,64	1,00		0,91	0,82
	TEC2	4,64	1,00		0,82	0,64
	TEC3	4,09	0,64		0,82	0,64
	TEC4	4,73	1,00		0,91	0,82
Sustainable Performance Scale	OPR1	4,91	1,00	0,91	0,64	0,27
	OPR2	4,82	1,00		0,64	0,27
	OPR3	4,64	0,91		0,91	0,82
	OPR4	4,73	1,00		0,82	0,64
	OPR5	4,55	0,82		0,91	0,82
	OPR6	4,91	1,00		0,91	0,82
	ENV1	4,27	0,73		0,82	0,64
	ENV2	4,27	0,73		0,73	0,45
	ENV3	4,55	1,00		0,82	0,64
	ENV4	4,55	0,91		0,73	0,45
	ENV5	4,73	1,00		0,82	0,64
	SOC1	4,73	1,00		0,82	0,64
	SOC2	4,36	0,82		0,91	0,82
	SOC3	4,18	0,64		0,82	0,64
	SOC4	4,82	1,00		0,91	0,82
	SOC5	4,82	1,00		0,82	0,64

AVG: average validity score
I-CVI: item content validity index
S-CVI: scale content validity index
UND: understandability ratio
UVR: understandability validity ratio

According to multiple authors, the acceptable I-CVI threshold for each item is 0,78 for six or more experts (Kim et al., 2020; Polit et al., 2007; Sunder and Prashar, 2020). In this context, all items met the criteria except for five (SUP3, TEC3, ENV1, ENV2, SOC3). The item SUP3 was revised with the experts' feedback, with the ones giving the lower rating agreeing that not only quality, but also cost and delivery are important criteria in most companies in supplier development and assessment processes. SUP3 question was therefore rewritten to not lesser the importance of the other two variables. After the revision, the experts were asked to review their ratings and I-CVI reached 1 (total consensus). ENV1, ENV2, and SOC3 were retained while being slightly below the threshold because of their high AVG value (above 4,18), which means that most experts deemed the question as "5: highly relevant", but I-CVI score was penalized by three experts choosing a value of "3: somehow relevant", which nevertheless confirms the validity of the question. Regarding item TEC3, when asking the experts who rated the question as "non-relevant", one of them effectively confirmed that it was because a typographical error and changed his rating, rendering the question valid under the revised score. The complete LM scale, and sustainable performance scale was considered valid with a S-CVI score of 0,91 on both cases, which is above the 0,90 threshold suggested by Ali et al. (2020) and Polit et al. (2007).

The understandability of each question was rated under the UVR criterion, which, according to Wan Ahmad et al. (2020) needs to be above 0,59 for eleven experts. This means that seven questions (PAP2, PAP3, SUP2, OPR1, OPR2, ENV2, ENV4) were deemed as "confusing" under this criterion. Since all those items were found relevant to the constructs under the CVI, they cannot be excluded from questionnaire. Instead, with the experts feedback they were rephrased to make them more understandable. Items PAP2, PAP3, SUP2 had some minor syntax changes with the help of the experts' feedback. On item OPR1, "cost" was specified as "manufacturing cost", and in OPR2 "quality" was specified as "scrap rate" following the suggestions of four experts. Finally, items ENV2 and ENV4 were deemed "confusing" by the same three experts. Their suggestion was not related to the question itself, but it was related to the item having an inverse answering scale, meaning that, for example, in the case of "solid waste generation", a decrease in the indicator is interpreted as a sign of improvement, therefore requiring a grading of 4 of 5 in the scale. Although how to answer reverse-scale questions was clearly stated in the questionnaire instructions, those items were marked with "*" at the end of the question. It turns out that Google forms uses a red "*" at the end of the question to mark mandatory items, which created the confusion. Reverse scale questions were then marked with a "^" and answering instructions were further specified.

In addition to assess the validity of each item, the Google Forms survey validation instrument developed at this stage had the aim of assessing the validity of the measurement scale and the sufficiency of each construct (i.e. if the asked questions are enough to properly represent the intended dimension (Hyrkäs et al., 2003)).

All questionnaire items are intended to be answered using a five-point Likert scale, however, the guidelines for the scale ratings are different in the LM constructs from those on the sustainable performance constructs. The reasoning for this differentiation in the scale guidelines is that, while the independent variable intends to measure the level of implementation of LM (therefore a none to high scale was needed), the dependent variable measures the improvement or detriment on sustainable performance (hence a centered scale is needed, ranging from high detriment to high improvement).

The different measurement scales are presented in Table 21 and Table 22. As thoroughly explained in Section 2.4.1, the survey employed in this research does not intend to measure the lean manufacturing implementation level by means of the level of implementation of some single set of practices, but by the level of achievement of lean goals instead, regardless of the set of practices employed by each company, as those can differ from one sector, culture, or manufacturing process to another.

Experts were asked if the measurement scale and guidelines were appropriate. Also, at the end of each construct, they were asked if the items were sufficient to properly measure the intended construct. Since in both cases the answer was dichotomous (i.e. "yes" or "no"), the agreement criteria was that at least 80% of the experts answered "yes", as proposed by Hyrkäs et al. (2003). The sustainable performance scale was considered acceptable by the experts' panel with an 82% agreement.

Table 21. Lean Manufacturing Likert scale guidelines

Rating	Level	Guideline
1	None	There have been no efforts and no practices have been implemented to achieve the lean goal
2	Low	Minimum efforts have been made to achieve the lean goal through a shallow implementation of few practices
3	Medium	Medium efforts have been made to partially achieve the lean goal through the implementation of some practices
4	High	High efforts have been made to successfully achieving the lean goal trough the effective implementation of lean practices
5	Superior	Significant efforts have been made to achieve an outstanding level of the lean goal through the implementation of world-class practices

Table 22. Sustainable performance Likert scale guidelines

Rating	Level	Guideline
1	Significant detriment	As a result of lean manufacturing implementation, the indicator performance has deteriorated significantly
2	Low detriment	As a result of lean manufacturing implementation, the indicator performance has deteriorated slightly
3	No change	As a result of lean manufacturing implementation, the indicator performance has not changed
4	Low improvement	As a result of lean manufacturing implementation, the indicator performance has improved slightly
5	Significant improvement	As a result of lean manufacturing implementation, the indicator performance has improved significantly

The LM scale was initially considered acceptable only by 73% of the experts. A follow-up with the experts thinking that the scale was unacceptable revealed that two of them thought that the scale should reflect the level of implementation of given lean manufacturing practices and not the efforts in pursuing a certain lean goal. After argumentation about the reasons why the present research does not intend to measure the implementation of specific lean practices or tools (as explained in sections 1.3.2, 1.3.3 and 2.4.1), both experts agreed that the scale was appropriate, but recommended to specify those reasons in the final survey instructions to clarify the scale meanings to the respondents. Interestingly, both experts traced their LM backgrounds to the Colombian automotive industry. During the 2000 decade, the main Colombian automotive assembly plants (Renault and Chevrolet) deployed a series of lean tools to their main suppliers in a rigid, step by step, universally applied program. As one of the experts suggested (and as it will be discussed in subsequent sections), this rigid LM adoption format led to many practitioners believing that LM was related only to the deployed tools even in some cases without being fully aware of their final goal. This expert conclusion further supports the approach of lean goals instead of specific practices adopted in this research.

Regarding the sufficiency of each construct, Table 23 presents the agreement percentage for each construct. Even though an agreement threshold above 60% can be considered for review when dealing with translated questionnaires (Moscoso Alvarado et al., 2020), three of the constructs were deemed “insufficient” by the experts (MGM, QLT, TEC). Sufficiency represents a complex balance between content validity and statistical aspects. While a larger battery of items could help to better represent and define the theoretical domain of an intended construct, the reliability of the SEM method (as well as most multi-variate analysis methods) relies heavily on the sample size, which in turn grows considerably with the number of observed variables involved.

Therefore, a larger amount of items on each construct probably leads to a higher sufficiency agreement among the experts, but will present considerable sampling problems later as the complete population of the study object is less than 800 companies (DANE, 2019) and average response rates in other LM studies involving survey data collection has been reported lower than 25% (Khanchanapong et al., 2014; Nawanir et al., 2018; Prasad et al., 2016). As a matter of fact, many of the most cited LM empirical studies in literature, such as those of Bortolotti, Boscari, et al. (2015), Dal Pont et al. (2008), and Shah and Ward (2003) (among many others), do not address the construct sufficiency validation, focusing only on item content validity from the semantic point of view, and convergent and discriminant validity regarding construct validity.

To cope with this situation, the participating experts were asked to join a conference call to debate around the reasons they thought rendered the constructs “insufficient” and find solutions that did not compromise the sample requirements later on. Initially, eight experts agreed to participate in the panel, but at last minute two of them were unable to take part in the conference call. However, among the six participating experts were most of the ones that disagree on the construct sufficiency. Regarding the management construct, one of the experts suggested that management commitment had to be present in “the assignment of a budget and necessary structure to implement LM”, and other suggested that “in many companies LM fails because managers are often present when launching a lean program or new practice, but they don’t do an extensive follow-up to ensure its maintenance”. With the above inputs, and after a refinement process of the proper redaction of the question, item 1.2.4 (MGM4) was included in the questionnaire, reaching a sufficiency consensus among the participating experts.

Table 23. Construct sufficiency

Variable	Construct	Coding	Sufficiency agreement
Lean Manufacturing	Human resources management	HRM	64%
	Management	MGM	27%
	Planning and processes	PAP	64%
	Supply	SUP	73%
	Quality	QLT	55%
	Technology	TEC	55%
Sustainable Performance	Operational	OPR	64%
	Environmental	ENV	64%
	Social	SOC	73%

On the other two constructs (QLT and TEC), the sufficiency agreement was initially higher, therefore, it was possible to reach a consensus without including new items on the questionnaire, but instead, rephrasing some of the existing ones to make them more comprehensive according to the experts’ suggestions. Regarding the technology construct, most of the discussion centered around item TEC3. Some of the authors approved the use of flexible manufacturing cells as a good proxy of LM, while others claimed that not necessarily a flexible manufacturing cell is the best solution for all processes or industries, and instead, the focus of a lean technology system should be the removal of bottlenecks to favor the process flow. A consensus was reached between the experts rephrasing the question to include both concepts depending on the case.

Some other minor syntax and form changes were made to few items and the instructions of the survey, from the suggestions of the experts. The expert’s reviews, both on the Google Forms instrument, the face to face and virtual interviews, and the final validation panel, also provided valuable insights regarding the methodological approach of the survey distribution, along with possible outcomes and explanations for the results. The final reviewed questionnaire is presented in Table 24, and the final version of the data collection instrument is attached in Appendix C.

Table 24. Final survey items

Variable	Construct	Code	Survey question	Spanish translation
Lean Manufacturing	Human Resources Management	HRM1	We have a structured continuous improvement culture that involves all the company	Existe una cultura de mejora continua estructurada que involucra a toda la compañía
		HRM2	We have autonomous work teams empowered to solve most of first-level problems quickly without consulting with their supervisors	Existen equipos autónomos de trabajo empoderados para resolver la mayor parte de los problemas de primer nivel rápidamente sin consultar con sus supervisores
		HRM3	There are standardized training programs for all personnel with tasks profiles are clearly defined according to the training level	Existen programas de entrenamiento estandarizado para todo el personal con perfiles de tareas claramente definidos de acuerdo al nivel de entrenamiento
		HRM4	Employees are trained to achieved multiple skills that allow them to perform multiple tasks in different workplaces	Los empleados se entrenan para desarrollar polivalencia que les permite desempeñar múltiples tareas en diferentes puestos de trabajo
	Management	MGM1	Manufacturing strategy is clearly defined and aligned with organizational strategy, and it is deployed to all company levels	La estrategia de manufactura está claramente definida y alineada con la estrategia organizacional, y se despliega a todos los niveles de la compañía
		MGM2	We have a 5S culture at all company levels with full top-management commitment	Existe una cultura de 5S en todos los niveles de la compañía con compromiso directo de la alta gerencia
		MGM3	We apply VSM techniques to all critical processes and actively perform efforts to minimize non-value-added activities	Se aplican técnicas de VSM (mapeo de la cadena de valor) a todos los procesos críticos y se realizan esfuerzos permanentes para minimizar las actividades que no agregan valor
		MGM4	The top management assigns resources for lean manufacturing implementation, and there is a follow-up of the perceived benefits	Se destinan recursos desde la alta dirección para la implementación de Lean Manufacturing y se hace seguimiento a los beneficios obtenidos
	Planning and Processes	PAP1	We apply efforts to reduce lot sizes for each product and manufacture just the exact quantities needed	Se realizan esfuerzos para reducir los tamaños de lote de cada producto y fabricar solo la cantidad exacta requerida
		PAP2	Process are clearly defined and standardized in order to achieve continuous one-piece flow with high cadence	Los procesos están claramente definidos y estandarizados con el fin de lograr un flujo continuo y una alta cadencia de fabricación
		PAP3	We use a short-term production planning with flexibility to quickly change the program in respond to actual demand	Se utiliza un plan de producción de corto plazo con la flexibilidad de cambiar la programación en respuesta a las fluctuaciones en la demanda real
		PAP4	Production planning and manufacturing system are organized in order to minimize the required WIP inventory	La planeación de la producción y el sistema de manufactura se organizan con el fin de minimizar el inventario requerido de producto en proceso
	Supply	SUP1	We are synchronized in real-time with our suppliers to receive materials according to production demand (pull system)	Se cuenta con una sincronización en tiempo real con los proveedores con el fin de recibir los materiales de acuerdo a la demanda de producción (sistema pull)
		SUP2	We have supplier development processes focused on achieving long-term, mutually beneficial relationships	Los procesos de desarrollo de proveedores se enfocan en alcanzar relaciones de largo plazo con beneficios para la empresa y el proveedor
		SUP3	Supplier evaluation and development is done not only based on prices, but also accounting for quality and delivery performance	La evaluación y selección de proveedores se realiza basada no solo en el precio, sino también en el desempeño de calidad y cumplimiento de entregas
		SUP4	Suppliers actively participate in new product development, and continuous improvement of current ones	Los proveedores participan activamente en el desarrollo de nuevos productos y el mejoramiento de los actuales

	Quality	QLT1	We are constantly surveying our customer needs and proactively doing efforts to exceed them	Constantemente se evalúan las necesidades de los clientes y se realizan esfuerzos proactivos por excederlas
		QLT2	We control all of our critical processes with SPC techniques to minimize variability	Se controlan todos los procesos críticos con técnicas de SPC (control estadístico de procesos) para minimizar la variabilidad
		QLT3	Quality performance information is updated, visible, and readily available to all personnel	La información sobre el desempeño de calidad se encentra actualizada, visible, y disponible para todo el personal
		QLT4	We have a quality management culture were all managers and employees accept their responsibility and commitment to quality	Existe una cultura de gestión de la calidad en la cual todos los administradores y empleados aceptan su responsabilidad y compromiso con la calidad
	Technology	TEC1	We are constantly doing efforts to reduce our set-up times	Constantemente se realizan esfuerzos para reducir los tiempos de cambio de referencia
		TEC2	We extensively apply TPM principles and perform preventive, predictive, and autonomous maintenance activities	Se aplican extensivamente los principios de TPM (mantenimiento productivo total) realizando actividades de mantenimiento preventivo, predictivo y autónomo
		TEC3	Our production system is configured in specialized flexible cellular manufacturing stations	El sistema de producción está configurado en células de manufactura flexibles, realizando esfuerzos constantes por eliminar los cuellos de botella
		TEC4	We constantly measure and monitor OEE performance (downtimes, cadence, quality) and use it as a decision-making parameter	Se mantiene un monitoreo y medición constante del OEE (tiempos de paradas, cadencia, calidad) y se utiliza como parámetro de toma de decisión
Variable	**Construct**	**Code**	**Indicator (English)**	**Indicator (Spanish)**
Sustainable performance	Operational	OPR1	Manufacturing cost^	Costo de fabricación^
		OPR2	Quality^ (scrap rate)	Calidad^ (nivel de rechazo)
		OPR3	Lot size flexibility	Flexibilidad en tamaño de lote
		OPR4	Production lead-time^	Tiempo de producción^ (lead time)
		OPR5	Cycle time^ (manufacturing cadence)	Tiempo de ciclo^ (cadencia de producción)
		OPR6	Work in process inventory^	Inventarios en proceso^
	Environmental	ENV1	Use of hazardous materials in production process^	Uso de sustancias peligrosas en procesos productivos^
		ENV2	Solid-waste generation^	Generación de residuos sólidos^
		ENV3	Green-house gas emissions^	Emisión de gases de efecto invernadero^
		ENV4	Energy efficiency in production processes	Eficiencia energética de los procesos productivos
		ENV5	Environmental regulation compliance	Cumplimiento a regulaciones ambientales
	Social	SOC1	Wages and economic compensation	Salarios y compensación económica
		SOC2	New direct and formal workplaces creation	Generación de nuevos empleos formales y directos
		SOC3	Employee turnover rate^	Tasa de rotación del personal^
		SOC4	Accident rate^	Tasa de accidentalidad^
		SOC5	Employee satisfaction and motivation	Satisfacción y motivación del personal

^: reverse scale items

3.2.2. Case Study

As part of the proposed methodology, presented in Figure 17 and Figure 24, a case study was performed which served two main purposes. First, to support the data collection instrument validation, and second, to gather firsthand insights on how lean manufacturing practices are applied in the context of the research object (i.e. Colombian metalworking industry) that could help to interpret the results of the collected data. Also, since the constructs definition, and the items (i.e. survey questions) selected to measure those constructs are also susceptible to be affected by cultural, process, size, and context gaps (as explained in Section 2.5.1), the case study will provide further content validity for the data collection instrument within the research object (Nawanir et al., 2018; Nordin and Belal, 2017). This approach is also justified by authors such as Bergenwall et al. (2012) and Shahbazi et al. (2018) who emphasize the importance of case studies when proper metrics and construct definitions are scarce in empirical research.

To select the proper company to conduct the case study, several factors were considered. First, it has to be a metalworking company, in order to be consequent with the research object and avoid context and process gaps, second, it has to be a Colombian owned company to close the cultural gaps. This is because many multi-national companies have corporate lean programs that develop and implement practices in the same way to all their facilities around the globe (Mollenkopf et al., 2010; Netland, 2016; Ocampo and Estanislao-Clark, 2014). Third, it has to be a well stablished company with at least 20 years of operation, and a considerable workforce size and annual turnover, to account for size gaps. Finally, it was expected that the selected company had an established and structured lean manufacturing program with some grade of success for at least 5 years to narrow the long-term orientation gaps, which gives enough time to overcome the 3 years lean desertion threshold evidenced by Resta et al. (2017).

Three companies located in the city of Manizales, Colombia were initially approached to participate in the case study and evaluate if their met the defined criteria as well as their availability to share their experience and data through their personnel. One of the companies declined due to strict internal confidentiality policies, while the other two were open to the researcher’s proposal. The selected company was the one that best met the designated criterions, and it was officially invited to participate in the case study with a written communication addressed to the general manager summarizing the main goals of the research, the methodology and objectives of the case study, and deliverables from the study. Said communication can be found on Appendix D (the company name and the contact person name were omitted for confidentiality purposes). In consideration, the company was offered a series of conferences about lean manufacturing state of the art, and a final report with the conclusions and recommendations derived from the case study, as well as early access to the final research results.

The company asked not to explicitly publish its name nor the name of their employees, and neither make specific remarks about their products or processes. However, they were fully open to the researcher, and authorized to publish the study results without censoring. As previously stated, the selected company is located in Manizales, and performs a series of metalworking processes ranging from machining to metal forming. It has more than 60 years in the market, with sales exceeding 20 million US dollars in 2018, and about 70% of those sales directed to the local market, and 30% to costumers in other countries (mainly in south and central America). By the time of the case study, it had more than 300 employees in their single facility, and had been implementing lean manufacturing practices for more than 8 years with mixed results, which becomes interesting to the purpose of the research since information about the critical failure factors is as valuable as that about the CSFs (Sunder and Prashar, 2020).

Most of the lean practices that the company had adopted were transferred from some of their customers belonging to the automotive industry, which in some cases deemed them as mandatory to their entire supply chain. The other practices were implemented through previous experience of some of the employees in other companies that had already implemented lean (most of them also from the automotive industry), and finally, over the course of the last eight years the company has also participated in several lean training initiatives for their personnel, some of them privately founded by the company, and some through local guilds and government agencies.

Prior to interviewing each group, a conference about general lean and sustainability concepts derived from the state-of-the-art literature was presented to the company participants. It was based on Henao et al. (2016) conference presented at the *5th World Conference on Production and Operations Management* and had the aim of giving a theoretical approach to lean manufacturing, explain where did the selected lean items came from, and settle grounds for discussion about the gaps between theory and the practical implementation given by the company. Afterwards, the three groups were separately approached with the goals described in Table 25.

The management level group was composed by top-management from the main company departments which included sales, logistics, manufacturing, and quality. The second group comprised tactical level employees which have the task of transforming the policies and directives given from the top management into day-to-day practices. In this group, the involved persons were narrowed to the functional areas that were more familiar to lean manufacturing practices: supply, quality, production, maintenance, deliveries, tooling, and research & development (R&D). Finally, at the operational level a group of factory floor operators was made available to the researcher for the study. That group comprised operators from a single production line, however, many of them were among the ones that had more years working for the company and were also most familiar with the lean tools implemented.

Table 25. Case study groups and goals

Group	Case study goal	Participants
Management	Determinate the relevancy of selected lean goals and understand the implementation strategies and their alignment to the business strategy. Evaluate the impacts on first order KPIs	4
Tactical	Identification of gaps between theory and practice on lean implementation, difficulties, and required adaptation of practices.	8
Operational	Identification of base perception about day-to-day impacts (positive or negative) of implemented practices, and the shop-floor adaptation process to them.	8

To enhance concentration of the participants, each group was boarded in multiple sessions over a course of a six weeks period. Two 2 hours sessions were held with the management group, three 2 hours sessions with the tactical group, and three 1-hour sessions with the operational group. In addition, the researcher participated in several lean-related activities developed by the company such as 5S sessions*, Kaizen* groups, standardized training, and autonomous maintenance. Over the course of each session, semi-structured group interviews were used, following the 5WH methodology on each question and letting the participants deliberate between them. Also, participants were asked if they though the items were relevant as part of the proposed lean constructs, and if they thought that each survey question was expressed in a language understandable to the average Colombia lean practitioner company (this validation was performed with the tactical group, where most of the participants had experience and were familiar with lean manufacturing practices, both from the studied company and from previous experience in other companies). At the end of the group sessions, remarks and conclusions were drawn by the researcher and discussed in a final 2 hours session with the management and tactical groups together to ensure the proper interpretation of the results and gathered conclusions.

The results were gathered into three main groups. First, those regarding the survey items validation, second, those related to the implementation, adaptation and efficacy of the implemented practices, and third, those concerning the possible explanations, CSF and CFF that could help with the interpretation of the research results. Regarding the item's relevancy, validity and understandability, there was a general consensus among the participants that all items were good indicators of the level of lean manufacturing implementation, and that were consequent with most of the lean goals pursued by the studied company, or other companies where they had previous lean experience. They also confirmed that the language and questions should be familiar enough to respondents among the research object that had at least some basic knowledge about lean manufacturing. These results were expected since they were previously analyzed by a thorough experts validation methodology exposed in Section 3.2.1. Another interesting remark from the panel was that they thought the survey approach of asking about the lean goals that a company is pursuing, regardless of the specific practices that each company is applying, render the survey instrument more generalizable across different sectors, processes or types of industries, since not all companies necessarily implement the same practices. This was specifically one of the main reasons for adopting this survey approach, as it was justified in Section 2.4, and the group opinion further supported that choice.

Regarding the second group of results, Table 26 summarizes the perceived level of implementation of practices pursuing each of the lean goals, the level of adaptation that was necessary to make from the original practice (as it was presented in literature, transferred from their costumers, or learnt in different workshops and seminaries), and the perceived efficacy of the implemented practices in positively affecting the pursued goal.

A further discussion of the results presented in Table 26 will be covered in some of the following sections, as well as the third set of results from the case study. Those will be discussed in light of the interpretation of the data gathered through the survey instrument and will support the discussion around the proposed research hypotheses. However, some important trends worth mentioning at this point derive from Table 26, which are important in light of the survey validation process.

First, the company has (at least to some extent) implemented practices pursuing almost all of the lean goals proposed, which supports that those goals are relevant in the research object. Interestingly, the only construct in which no practices were implemented, related to supply. When asked about the reasons, the participants argued that most supply activities were coordinated and executed by a third-party company that belonged to the same holding of companies and coordinated supply activities at corporate level for different plants. Therefore, the studied company did not have much influence on the supply related practices as they were corporate mandated. However, they acknowledge that the company which outsourced the supply probably was pursuing most of those goals, but there was little knowledge behind their strategy.

Table 26. Implementation, adaptation, and efficacy of lean practices on the studied company

Bundle	Lean goal / principle	I	A	E
Human Resources Management	Promote a continuous improvement culture	++	+	+
	Promote leadership and empowerment of work teams to autonomously and quickly solve problems	+	+	+
	Create a clear definition of tasks and roles with standardized training processes	++	++	++
	Develop multi-skilled personnel with cross-training capabilities	++	++	++
Management Commitment	Alignment between manufacturing strategy and business strategy			
	Top-management driven 5S culture	+		
	Clear efforts to eliminate non-value-added activities at all organizational levels and processes			
	Assignation of resources for lean implementation, and top management follow-up of the results	++		+
Planning and Processes	Lot size reduction	++	+	+
	Standardized and continuous process flow	+	+	+
	Short-term, demand-driven (pull) production planning	++	++	++
	WIP inventory reduction	+	++	+++
Supply	Use of pull systems to achieve a demand-driven low inventory supply			
	Supplier development for long-term win-win relationship			
	Supplier selection based on quality, delivery and price			
	Supplier involvement in new product development and improvement			
Quality	Proactively seeking to exceed customer expectations			
	Use of SPC to reduce variability	+++	+	++
	Available and updated quality performance information	+++	+++	+++
	Top management commitment to quality	++	+++	+++
Technology	Setup times reduction	++	+	+
	Application of TPM principles	+	+	+
	Specialized manufacturing stations and cellular manufacturing	++	+++	++
	Constant monitoring and improvement of OEE	++	+++	+++

I: Implementation level; **A**: Adaptation level; **E**: Efficacy level
+: Low level; **++**: Medium level; **+++**: High level

Second, as lean practices can be often divided into “soft” (i.e. those related to the people, culture, and ways of doing things) and “hard” (i.e. those related to the machines, processes, and equipment) practices (Bortolotti, Boscari, et al., 2015), there was a tendency on the studied company to have a higher level of implementation on “hard” practices, particularly those related to technology, quality, and, planning and processes constructs. When asked about the reasons for this trend, some of the participants argued that it can be related to the cultural change required for implementing many “soft” practices that often alter long traditions related to the way of people doing things (they posed 5S as an example), in contrast to “hard” practices being in some cases more related to investments and technology development or application. This supports the importance of considering cultural, process and context gaps when developing and validating the data collection instrument.

Finally, from the four practices that presented a high level of efficacy on positively impacting the pursued lean goal, three had also a high level of adaptation (and the other a medium level). And from the five practices that presented a medium level of efficacy, four of them presented at least a medium level of adaptation. This present a trend that suggests that the positive results of a practice implementation not only depends on implementing it “according to the book”, but depends also significantly on adapting it to cope with each company context, culture and structure, a notion that has been suggested by Netland (2016). This result is also significative as it further justifies the goal-oriented approach of the developed survey, instead of a practice-oriented approach (i.e. asking companies if they have implemented a particular practice or tools), because in the latter, there can be a bias related to adaptations that each company can have done to practices that render them significantly different from the original one.

3.2.3. Pilot Test

Prior to distributing the final test to the selected sample, a pilot test was applied to a small, non-random sample of companies. A total of 65 companies were contacted directly using e-mail, telephone, and WhatsApp. Since convenience sampling was employed and the resulting sample lacks statistical significance, it can be argued that a “pre-test” was conducted instead of a “pilot test” (Babbie, 2010). However, in OM research the term “pilot test” or “pilot study” is more commonly employed (Alhuraish et al., 2017; Lai et al., 2013; Zhou, 2016) to define a non-definitive administration of the survey instrument merely for validation purposes, instead of for data collection purposes (Dieste et al., 2020; Moscoso Alvarado et al., 2020).

The survey was targeted to production, operations, quality or general managers, as suggested by Garza-Reyes et al. (2018). However, in some companies, other positions with extensive knowledge of lean manufacturing and company performance related measures were also considered as respondents. The designed data gathering instrument (found on Appendix C) was implemented on-line via Google Forms, for self-administration in most cases. However, a total of 15 cases at this stage were personally administered (also using the Google Forms platform) in order to gather valuable insights regarding understandability, usability, error proofing, completion time, and improving the questions, format, and scales (Creswell, 2014; Prasad et al., 2016). Initial contact via e-mail and telephone produced a relatively small response rate, close to 50%. Afterwards, most contacts were stablished using WhatsApp and directly sharing the Google Forms link so that respondents could answer from their smartphones. This strategy proved highly effective, as response rate surpassed 90%.

After achieving 60 valid responses, no more surveys were distributed at the pilot stage, since the sample was deemed already sufficient according to standards employed in previous similar research in the same field (Abolhassani et al., 2016; Abu et al., 2019; Awan, 2019; Prasad et al., 2016). The main goal of the pilot test was to validate the understandability of the survey items and measurement scales, the usability of the Google Forms platform, and the total completion time, prior to administer the final questionnaire the defined sample. Although many of these topics were already tested and proofed following the methodology described in the previous sections, it is important to notice that the understandability of the questions was validated by experts in the field that are supposed to be highly familiar with the Lean and Sustainability terminology and concepts. On the other hand, the pilot test allowed to provide further validation of the aforementioned topics by the “general public” to which was addressed the survey in the respondent companies, that is, the target population (Chavez et al., 2015).

Another important result from the pilot test relates to the selected constructs validation. Since the pilot test sample is relatively small, the entire measurement scale cannot be validated at this stage. However, each one of the constructs for both Lean Manufacturing and Sustainable performance can be tested separately for reliability and, discriminant and convergent validity. As discussed in Section 3.2, reliability relates to how the different items comprising a single construct are “aligned” towards a single dimension. Convergent validity tests if all single items in a construct are closely enough related to each other to form a valid construct, while discriminant validity means that items from different constructs are sufficiently different from each other to ensure that one item is not giving a measure of two or more constructs (Vargas-Halabí et al., 2017).

To test the internal consistency and reliability of the measurement model, the Cronbach's α was calculated for each construct, resulting in adequate levels for all of these (above 0,7) in accordance with Kim et al. (2020) and Prasad et al. (2016), with the results reported in Table 27 for the LM constructs and Table 28 for those of sustainable performance.

Table 27. Lean manufacturing scale reliability and validity (pilot test)

Construct	Code	Eigen value	% Variance	Factor loading	Cronbach's α	AVE
Human resources management	HRM1	2,109	9,587	0,816[a]	0,744	0,713
	HRM3			0,866*		
	HRM4			0,850*		
Management	MGM1	3,051	13,866	0,842[a]	0,753	0,696
	MGM2			0,812*		
	MGM3			0,820*		
	MGM4			0,861*		
Planning & Processes	PAP1	2,926	13,302	0,833[a]	0,828	0,682
	PAP2			0,749*		
	PAP4			0,890*		
Supply	SUP1	2,626	11,935	0,633*	0,798	0,498
	SUP2			0,654*		
	SUP4			0,815[a]		
Quality	QTL1	3,732	16,964	0,844*	0,820	0,779
	QTL2			0,890*		
	QTL3			0,891*		
	QTL4			0,905[a]		
Technology	TEC1	1,920	8,729	0,860*	0,823	0,666
	TEC2			0,877*		
	TEC3			0,758*		
	TEC4			0,762[a]		

[a]parameter fixed at 1; *p<0,001
Model fit: χ^2=192,538 (183df) (p=0,300 >*0,05*); χ^2/df=1,052 <*3*; CFI=0,739 >*0,9*; RMSEA=0,028 <*0,08*

Table 28. Sustainable performance scale reliability and validity (pilot test)

Construct	Code	Eigen value	% Variance	Factor loading	Cronbach's α	AVE
Operational performance	OPR1	5,451	38,934	0,755[a]	0,848	0,493
	OPR2			0,785*		
	OPR3			0,575*		
	OPR4			0,636*		
	OPR5			0,742*		
	OPR6			0,695*		
Environmental performance	ENV1	1,875	13,396	0,768[a]	0,839	0,585
	ENV2			0,947*		
	ENV3			0,673*		
	ENV5			0,630*		
Social performance	SOC1	1,504	10,744	0,768[a]	0,771	0,481
	SOC2			0,634*		
	SOC3			0,609*		
	SOC5			0,746*		

[a]parameter fixed at 1; *p<0,001
Model fit: χ^2=93,487 (74df) (p=0,063 >*0,05*); χ^2/df=1,263 <*3*; CFI=0,955 >*0,9*; RMSEA=0,058 <*0,08*

To test the validity of the proposed constructs (i.e. convergent and discriminant validity) a confirmatory factor analisis was performed (CFA). Since the employed data collection instrument was purposed-designed for this research, and all the indicators (observed variables) were retrieved from an extensive literature review and validated through a panel of experts, a CFA approach is appropriate for construct validation (Bagozzi and Yi, 2012), as opposed from an exploratory factor analisis (EFA) approach more commonly employed when retrieving constructs from secondary data (i.e. data from a survey that was not directly designed for the present study). As previously discussed, due to sample size being small at this pilot stage, two separate measurement models (one for each second order construct) were proposed and the CFA process was applied independently to each one of them, in accordance with Figure 21 and Figure 23.

As a first step of the CFA, a principal component analysis (PCA) was performed using IBM SPSS 23 to verify that the number of proposed constructs effectively explains a large enough amount of the total variance of the data (Sunder and Prashar, 2020). Factors with eigenvalues above 1 were retained according to the Kaiser criterion (Prasad et al., 2016). The results confirm the proposed structure of six factors for the LM construct, and three factors for the sustainable performance construct, as presented in Table 27 and Table 28, along with their corresponding percentage of variance explained. For the LM construct, a varimax rotation with Kaiser normalization was applied to the data to improve factor loadings and total variance explained, resulting in the proposed factors explaining 74,384% of the total variance. For the sustainable performance construct, all items presented adequate factor loadings (above 0,5) without the need for a rotated solution, resulting in a 63,074% of total variance explained by the non-rotated solution.

As a second step of the CFA, both measurement models were tested using IBM SPSS AMOS 23 structural equation modeling (SEM) software. To confirm that the data sample appropriately fit the proposed models (therefore confirming that the measured items are reflected in the first order constructs), common goodness-of-fit indicators were employed and confronted against their correspondent thresholds, according to literature. Fit values for each model are shown at the bottom of Table 27 and Table 28 and can be considered acceptable at this pilot stage, in accordance to Chavez et al. (2015) considering that a lower than ideal fit is expected for the small data sample of the pilot survey (Curran et al., 2003; Fullerton et al., 2014). A generalized least squares (GLS) estimation method was employed instead of a maximum likelihood (ML) method because for pilot-testing purposes, multivariate normality assumptions were not considered, in which case, GLS tends to produce better empirical fit (Olsson et al., 2000; Yuan and Kano, 2018).

It is important to notice that the CFA approach through SEM follows an iterative approach until achieving a satisfactory fit of the proposed models. In this case, the LM measurement model was initially tested with all survey items leading to a poor model fit, as it was the case of the sustainable performance measurement model considering all items. Therefore, items with low factor loadings were eliminated on each iteration until achieving acceptable fit indices, and after confirming that the elimination of more items did not produce a significant improvement in the comparative fit index (CFI). This was the case for HRM2, PAP3, and SUP3 in the LM construct, and ENV4 and SOC4 in the sustainable performance scale. Finally, in the LM construct the CFI was slightly lower than the expected threshold, however, the other fit indicators presented more than acceptable values, therefore, the solution was retained after verifying that further elimination of items or alterations to the model did not produce a sensible improvement of CFI.

After assessing the reliability and consistency of each measurement model, convergent validity can be tested using the average variance extracted (AVE) for each construct, which is reported on the last column of Table 27 and Table 28. The obtained AVE for each construct was well above (or close to in the case of SUP, OPR, and SOC) 0,5 (Sardana et al., 2020). Fornell and Larcker (1981) originally suggested the AVE as an appropriate measure of discriminant and convergent validity and recommended a threshold above 0,5. However, in certain cases (especially in purpose designed questionnaires applied to small pilot samples) AVE values slightly below 0,5 can be considered acceptable (Burawat, 2019; Kim et al., 2016), as long as the shared variance between constructs remains lower than each constructs AVE. Therefore, the convergent validity of all constructs was deemed appropriate at this point, with the AVE values expected to raise in the final data sample.

The performed tests and obtained results were considered acceptable enough at the pilot stage to conclude that the survey instrument is appropriate to continue being further distributed to the complete sample of companies comprising the study object of this research. While some items were removed from the constructs (HRM2, PAP3, SUP3, ENV4, and SOC4) to provide better model fit at this stage, it was decided to keep all the survey items into the final instrument to be applied, as the pilot-test AVE and fit indicators do not deteriorate too extensively. Also, when reviewing these results with some of the experts participating in the validation of the survey instrument, it was concluded that the probability of respondents being misled by keeping all items was scarce, and that those items could be removed from the final analysis if they continued to present a low factor loading in the final data set anyway.

3.2.4. Common method bias

One important concern when dealing with survey-based research, is the common method bias (CMB). CMB can result in unexpected and unreliable results when independent, dependent, and control variables are collected using the same method (Jordan and Troth, 2020). To deal with CMB, several approaches have been proposed, however, some of them have practical restrictions that can negatively affect other aspects of the research. For example, Shrafat and Ismail (2019) suggest that using multiple respondents to gather data from a single source can significantly reduce CMB. However, as it was already pointed out by Sardana et al. (2020), gathering survey data from companies is already challenging, hence, if further requirements, as multiple respondents are included, less companies will be willing to cooperate with the research, then, hampering statistical power as a consequence of a smaller sample.

To deal with CMB a practical approach was employed considering three strategies derived from state-of-the-art literature. First, Gimenez et al. (2012) and Longoni and Cagliano (2015) suggest that anonymity and confidentiality of the respondents must be guarantee. This makes respondents more confident when having to give undesirable answers (like acknowledging that performance has declined). Second, an expert’s method was used to guarantee that questions were clear, concise, and easy to understand, avoiding complicated syntaxis and the use of confusing or ambiguous terminology (MacKenzie and Podsakoff, 2012).

Finally, procedural strategies to reduce CMB were also adopted as suggested by Jordan and Troth (2020). These include an instructions and purpose of the research section at the beginning of the questionnaire, a different measurement scale for the dependent and independent variables, and the inclusion of some reverse-coded items. Finally, the principal components analysis (described in

Section 3.5.1) shows that no single construct explains more than 50% of the total variance extracted, which is a good indicator of a low CMB (Kamble et al., 2020; Sardana et al., 2020).

3.3. Sample definition and data collection

As it was previously stated, the proposed hypotheses of the present research are intended to be validated for the Colombian metalworking industry. The importance of Colombian metalworking industry to the country development was highlighted in Section 1.7, as it contributes to about 13% of the country industrial GDP and about 13% of all industrial workplaces, but at the same time suffers from scarce research regarding how to improve its competitiveness and sustainability. Therefore, it is expected that the selected population can profit from the results of the present research, as well as academics and government institutions.

3.3.1. Population description

To achieve a proper characterization and census of the Colombian metalworking industry has been proved a difficult task. First, there is no official definition of which companies can be considered metalworking companies among the Colombian industry. The *Departamento Nacional de Planeación* (2004) (National Planning Department), made a first attempt to define the metalworking sector as composed by two groups of companies. The first change the shape and volume of metals trough mechanical deformation, and the second manufactures non-electric industrial machinery trough the assembly of parts, most of them being metallic. According to the cited report, production was composed mainly by manual mills, manual shaving machines, machetes, pressure cookers, cooking pots, nails, barbed wire, pressure vessels, door locks, screws, office furniture, industrial machinery parts, and elevator parts. This classification nonetheless has been proven inaccurate, because it does not include the siderurgy chain which was sufficiently developed by the end of the twentieth century, and because it also leaves outside other developed sectors such as the automotive industry and the electrical equipment manufacturing (electric motors and power transformers).

Gutiérrez (2010) proposed an updated classification of the metalworking sector based on the ISIC (International Standard Industrial Classification) codes (presented previously on Table 1.7), which indeed included the automotive industry, industrial electric equipment, and iron and steel works. However, this classification was outdated by the time of publication since it was based on the third revision of the ISIC classification which was replaced (and significantly revised) by the fourth, and current, revision by 2008. Nevertheless, Gutierrez classification, sets an important base for a proper definition and delimitation of the metalworking industry since it is based on internationally employed ISIC codes.

Even the report of Ramirez et al. (2011), appointed by the ANDI's Fedemetal chamber (Colombian industrial guild chamber for the metalworking sector), was still based on the third revision of the ISIC codes. They proposed two main branches for the sector: metallurgy and metal works. Metallurgy relates to the basic transformation of metallic raw materials, and metalworks relates to further processing of such raw materials to obtain finished products for different markets. However, Ramirez et al. report is biased by the omission of the automotive industry (which in Colombia is comprised by several metalworking companies), since the automotive supply chain is associated under a different commerce guild called ACOLFA (*Asociación colombiana de fabricantes de autopartes* – Colombian autoparts manufacturers association).

There are more recent studies and publications around the Colombian metalworking industry such as those of Figueredo Garzon et al. (2020), Morelos-Gómez et al. (2021), and Sanabria (2014), which however do not attempt the realize a proper characterization or definition of the sector. The most comprehensive characterization of said industry to date, possibly, is that of Preciado Hernández et al. (2018) report. They propose three main links comprising the metalworking chain, being supply, transformation, and commercialization, which are presented with their corresponding number of companies in Table 29. This classification is the only one, to the author knowledge, that groups the Colombian metalworking industry according to the current revision of ISIC codes.

Table 29. Composition of Colombian metalworking industry by company size.

Link	**Category**	**Number of companies**					
		Small	**%**	**Medium**	**%**	**Large**	**%**
Supply	Raw material wholesale	295	4,9	103	6,3	65	12,9
	Raw material extraction	96	1,6	26	1,6	16	3,2
Transformation	Manufacturing services	101	1,7	8	0,5	5	1,0
	General use products	373	6,3	102	6,2	26	5,2
	Machinery products	258	4,3	68	4,2	10	2,0
	Motion industry products	39	0,7	7	0,4	6	1,2
	Agriculture products	24	0,4	5	0,3	3	0,6
	Automotive industry products	216	3,6	52	3,2	25	5,0
	Household products	20	0,3	8	0,5	5	1,0
	Structural products	422	7,1	85	5,2	15	3,0
	Industrial products	63	1,1	28	1,7	2	0,4
Commercialization	Distribution and sales	4.036	67,9	1.143	69,9	325	64,6
Total		**5.943**		**1.635**		**503**	

Adapted from: (Preciado Hernández et al., 2018)

The supply link comprises all the extraction and refinery (often called basic industries) of metals, which are mainly iron and steel (siderurgy). The transformation link is the more complex one. It manufactures different finish products from raw materials obtained in the supply link, using diverse metalworking processes described in Figure 26. The main market sectors that consume such products are industrial, automotive, agriculture, home appliances, and structures. Finally, the commercialization link deals with the wholesale or retail distribution and sales of the finished products obtained from the previous link.

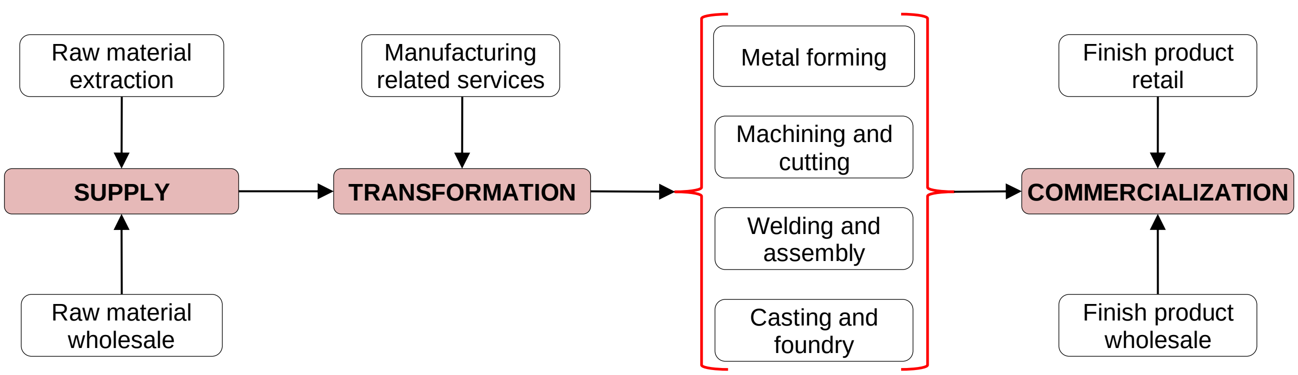

Figure 26. Colombian metalworking chain. *Adapted from: (Preciado Hernández et al., 2018)*

This research will focus on companies belonging mainly to the transformation link, as those are the most prone to implement lean manufacturing practices considered in this study. However, some companies belonging to the commercialization and supply link will be considered as long as they perform manufacturing (or by defect, metal transformation) processes, which is the case, for example, of siderurgies and foundries.

It is also highly important to consider that for the purposes of this research only companies with more than 10 employees will be considered, hence leaving personal and micro enterprises outside of the selected sample. There are three main factors that justify this decision. First, evidence points to about five years being required for a proper implementation of lean manufacturing (Čiarnienė and Vienažindienė, 2014), but smaller enterprises tend to be younger in age, and therefore are less prone to have properly adopted lean manufacturing practices. There is also evidence that smaller companies are less prone to fully implement lean manufacturing (Shah and Ward, 2003; Zhou, 2016). Second, companies with less than 10 employees are usually less prone to be concerned about sustainability issues, and in most cases, are mainly focused on short-term economic survival (Al Awadhi, 2020; Bakos et al., 2020; Sajan et al., 2017). And third, there is concern regarding the dificulty of getting appropriate and reliable data from smaller companies, as the intended survey respondents (managers) are often facing high workloads derived from managing multiple processes, leaving short time to help with academic purposes, and might not be even familiar with the questionnaire terminology as their companies are less prone to be concerned over sustainability or lean manufacturing practices (Negrão et al., 2017; Ramirez-Contreras and Faaij, 2018).

With the aforementioned considerations regarding the objective population delimitation, from the data in Table 29, an approximate of 113 large companies fall between the proposed parameters (company size, and metalworking sector link), along with 389 medium enterprises, and finally, 1.612 small ones, for a total population of 2.114 Colombian metalworking companies according to Preciado Hernández et al. (2018) recollection. This data seems overestimated when compared with information collected from the 2019 round of DANE's EAN (*Encuesta anual manufacturera* – Annual manufacturing survey), using the ISIC classifications listed in Table 30.

Table 30. Composition of Colombian metalworking industry by ISIC codes and company size.

ISIC	Description	Small	Medium	Large	Total
241	Manufacture of basic iron and steel	88	8	4	100
243	Casting of metals	10			10
251	Manufacture of structural metal products, tanks, reservoirs and steam generators	171	14		185
259	Manufacture of other fabricated metal products; metalworking service activities	256	27		283
271	Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus	59	8		67
272	Manufacture of batteries and accumulators	4	3		7
273	Manufacture of wiring and wiring devices	3	4		7
274	Manufacture of electric lighting equipment	22			22
275	Manufacture of domestic appliances	13	5		18
279	Manufacture of other electrical equipment	32			32
281	Manufacture of general-purpose machinery	169	12		181
282	Manufacture of special-purpose machinery	115	8		123
291	Manufacture of motor vehicles	4		4	8
292	Manufacture of bodies for motor vehicles; trailers and semi-trailers	39	5		44
293	Manufacture of parts and accessories for motor vehicles	75	9	3	87
309	Manufacture of transport equipment n.e.c	22	3	7	32
Total companies		**1.082**	**106**	**18**	**1.206**

Elaborated with data from: (DANE, 2019; United Nations, 2008)

The data from 2019 EAN (presented in Table 30), shows that Colombian metalworking industry is composed by 1.206 registered companies, from which 18 are large (more than 800 employees), 106 are medium (between 251 and 800 employees), and 1.082 are small companies (between 10 and

250 employees). The small companies provided employment (on 2019) to 51.528 individuals, while the medium companies employed 43619, and the large ones 14.464. The total production output amounted $31.520 billion COP (about $9,2 billion USD), with large companies accounting for 36%, medium 38% and the small ones 26% of the total. Finally, most companies are concentrated in the main populated areas of the country, comprised by Bogotá and its surrounding towns (Cundinamarca department[8]), the Antioquia region, along with the coffee axis (Caldas, Quindío, and Risaralda departments), the Cauca Valley, the Atlantic coast region (Bolivar and Atlántico departments), and the Santander's region, as presented in Table 31. This region-wise distribution is consistent with the one proposed by Gutiérrez (2010).

Table 31. Distribution of Colombian metalworking industries and workplaces by department.

Department	Number of companies	Workplaces distribution
Bogotá	546	27,3%
Antioquia	281	25,9%
Valle	139	9,7%
Cundinamarca	128	13,6%
Santander	49	3,5%
Atlántico	41	6,4%
Caldas	26	5,1%
Risaralda	23	2,2%
Bolívar	15	1,2%
Boyacá	15	3,2%
Norte Santander	8	0,3%
Cauca	6	1,3%
Quindío	4	0,1%
Tolima	3	0,1%

Elaborated with data from (DANE, 2019)

3.3.2. Sample definition

As previously stated, there is no publicly available census for the Colombian metalworking industry. Although the EAN offers relevant statistics on production, employment, energy consumption, location, assets, and other data, according to each ISIC code, the information is presented population-wise and anonymous, rendering useless for sampling selection purposes.

As an alternative to the aforementioned problem, individual companies' data was taken from the chambers of commerce registries. Colombian legislation states that all companies independent of their size and commercial activity must be registered in their corresponding chamber of commerce (according to the city or region where the company is operating), providing general information about the company, including their main economic activity (according to ISIC codes), and their number of employees (among other information, that its non-relevant to the present sample delimitation). Each company's chamber of commerce registry must be renewed with updated information each year for as long as the company is legally constituted, regardless of if it is operating or not.

Part of the companies information registered in the chambers of commerce is available to the general public by paying a designated fee, which is usually associated to the number of registries (one registry equals one company) that the customer wants to access. For this research, information was accessed in the first semester of 2020 through the *Camara de Comercio de Bogotá* (Bogota chamber of commerce) on-line platform which keeps information from companies registered in 44 chambers

[8] In Colombia, administrative regions are called "departments".

of commerce in all Colombia, including those comprising the regions where most metalworking companies are condensed (presented in Table 31).

The selected registries were sorted according to company size (including only small, medium, and large enterprises) and ISIC division included in Table 32 (including every corresponding ISIC groups and classes). This resulted in 1.176 companies matching said criterions, with 80 of them being large companies, 206 medium, and 890 smalls. Said data is fairly consistent to that of 2019 EAN presented in Table 30. The difference between each category of company size could be explained because of the size classification criterion. Whilst company size data from the 2019 EAN was sorted in accordance with their number of employees, by December 2019 the 957-decree issued by the Colombian Ministry of Commerce, Industry, and Tourism, unified previous company size classification criterions to one based on each company income during the previous year.

Table 32. Chambers of commerce registry of companies by ISIC codes and company size

ISIC Division	Description	Large	Medium	Small	Total
C243	Casting of metals	2	7	21	30
C25	Manufacture of fabricated metal products, except machinery and equipment	23	80	455	558
C27	Manufacture of electrical equipment	17	27	94	138
C28	Manufacture of machinery and equipment n.e.c.	10	46	189	245
C29	Manufacture of motor vehicles, trailers and semi-trailers	25	43	110	178
C30	Manufacture of other transport equipment	3	3	21	27
Total companies		**80**	**206**	**890**	**1.176**

To narrow down the sample, only active companies (i.e., companies that are still operating by the time of their last registry renewal) were considered, and the search was also limited to companies whose registry was last renewed in 2020 or 2019[9] to filter for extinct companies. This resulted in a final selection of 993 companies. The complete database of selected companies downloaded from the Bogotá Chamber of Commerce platform can be found in Appendix E. A further refinement of the list excluded companies that did not performed manufacturing operations and metal transformation processes. According to the selected ISIC codes, only manufacturing companies were supposed to be included on the list, however after further inquiry on the companies website, or after contacting them directly a total of 178 companies were deemed outside the objective population. Most of them, performed manufacturing processes in the past (hence the registered ISIC code) but became commerce companies (mainly importing and distribution) in recent years. With this sorting, the final population was comprised by 815 companies.

The present research uses a random sampling approach, instead of a convenience sampling approach. In a random sampling approach (also called systematic or probabilistic sample), each individual from the objective population has the same probability of being included in the sample, regardless of any specific parameters that might impact the outcome of the research. In this case, conclusions drawn from a representative sample can be generalized to the population (Creswell, 2014). In a convenience sample (or non-probabilistic sample), individuals are chosen according to their availability or other parameters that might impact the outcome of the research. In said case, the results cannot be properly generalized to the entire population. However, convenience sample is

[9] By the time of the search, due to the coronavirus pandemic, many companies, whilst still operating, had chosen not to renew their chamber of commerce registry to save costs. This registry renewal extension period was one of many measures adopted by the government to help companies deal with the COVID-19.

often adequate for theory-testing purposes (Peterson and Merunka, 2014), in other words, to conclude if a given theoretical proposition applies to a given group of individuals, based on the premise that such population is ruled by that theoretical statement (Leiner, 2016).

Given that the complete population census is available, and that the individuals list is relatively short (in the sense that is relatively manageable to reach each individual to ask them to participate in the research) (Creswell, 2014), a random sample approach fulfills all the objectives of this research, not only regarding the test of the proposed hypotheses, but also to provide useful guidelines to government institutions to implement public policies aimed to improve the country's manufacturing companies' competitiveness without compromising their sustainability. Also, it is expected that the results might be useful to managers and practitioners in order to successfully implement lean manufacturing practices that allow them to improve their performance in a "balanced" way between all three TBL pillars. To achieve said outcomes requires some level of results generalization that could only be achieved through a random sampling process.

3.3.3. Data collection

The final survey was distributed via e-mail to all suitable companies referenced in Appendix E. The web-based massive e-mailing distribution platform MailChimp[10] was used to send the invitation letter containing the link to the purpose-designed Google Forms questionnaire. The invitation letter was addressed to the contact e-mail registered in the chamber of commerce database. A model of the invitation e-mail can be found on Appendix F. The first mailing round was sent in January 2020, with a follow-up e-mail in February. The initial response rate was about 8%, so a second round was scheduled for March. By the time of the second round the Coronavirus pandemic had already reached Colombia, with the country entering a full quarantine by the end of March and all companies (except those related to the food supply and medical supply chain) temporarily ceasing activities.

The COVID-19 pandemic and the subsequent lockdown in Colombia (which lasted for several months) severely impacted the response rate of the survey. The second round was then sent in May 2020 when the regulations allowed for non-essential manufacturing activities to resume operations, however under strict biosecurity protocols and with reduced capacity. This second round produced an even lower response rate (about 3,4%), which was probably due to most companies focusing by the time on survival in the face of a contracted demand and a difficult economic situation. This required a different approach, which was more time consuming, but proved more effective. This new approach included contacting each company individually using e-mails registered in their website (if different from those on the database), or by telephone. Many of the telephone numbers registered in the database were found outdated. In that case, the updated telephone number was taken from the company website when available.

After contacting each company by telephone and asking for the available intended respondent (general, operations, production, quality, engineering, or similar, managers, or other personnel with sufficient knowledge of the company's manufacturing strategy and its performance at different levels), the link to the questionnaire was then sent to each individual e-mail, or via WhatsApp (at the respondent choice). The WhatsApp strategy proven more effective as the respondents were able to directly access the link and answer the survey from their smartphone. In parallel, LinkedIn was used

[10] https://mailchimp.com/

to search for potential respondents that reported to work for the target companies on their profile, and then, they were contacted with the survey link directly through the LinkedIn platform. This approach was also proven effective, with more than 70% of the contacted individuals answering the survey. It was however highly time consuming and not all companies were listed on LinkedIn. In addition, all respondents were asked to forward the survey to their colleagues from other metalworking companies to broaden the coverage.

Finally, a third round of the survey was sent in October 2020, when most industrial activities were again operating at “normal” levels, although biosecurity protocols were still strict, and some mobility restrictions were still in place in Colombia. With all the combined efforts by December 2020 a total of 133 valid responses were achieved, including all valid results from the pilot test which were conserved as part of the final sample since the data collection instrument was not modified. This allowed for a final response rate of 16% which was deemed adequate in light of previous similar research in the field (Jabbour et al., 2013; Sardana et al., 2020). The final response rate is also sufficient for the achievement of some level of result generalization (Abu et al., 2019; Chatzoglou et al., 2018; Sajan et al., 2017).

It is likely that the COVID-19 pandemic prevented from achieving a higher response rate. Also, as Sardana et al. (2020) points out, there are several challenges associated with the collection of primary data from survey studies, especially in developing countries, a phenomenon that could be related to the lesser importance, perceived by managers, of scientific development and sustainability-related issues, with respect to their day-to-day operational responsibilities (Katiyar et al., 2018).

3.4. Descriptive Results

Before examining in depth the quantitative results from the survey, a description of the sample companies is presented in this section, which allows to understand and better interpret the results presented later. Along with the survey items comprising the measurement model, a section of categorizing questions was included at the end of the survey, although, some of them were optative, as was the case of the responded name, company name, e-mail, etc. It is important to mention that all received surveys were deemed valid responses. This was helped by the fact that all survey items (for the measured variables) were obligatory fields in the Google Forms instrument, therefore preventing from having missing data. The complete survey results for each company can be found in Appendix G. To protect the privacy of the respondents, three survey fields were excluded from the appendix: “name”, “e-mail”, and “company name”.

The final sample is composed mainly of small companies, ranging from 10 to 50 employees (40%), along with other 24% ranging from 51 to 200. Medium companies account for 18% of the sample, and the remaining 18% is comprised by large ones (see Figure 27). This distribution of the samples was expected as a result of the probabilistic sampling process employed, in which, the obtained distribution resembles that of the population presented in Table 32.

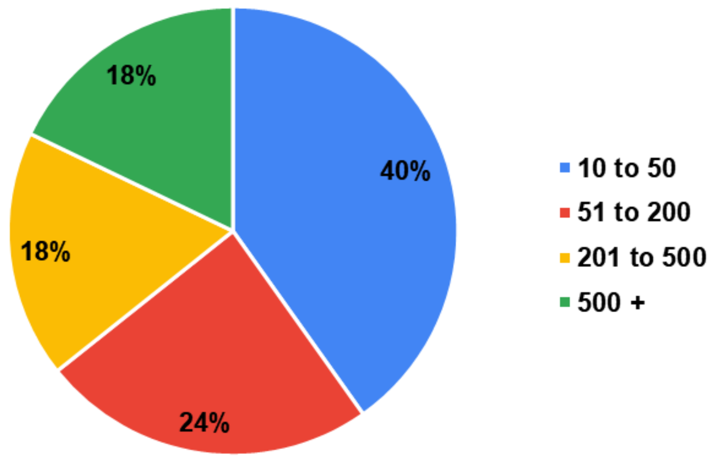

Figure 27. Sample distribution by number of employees

Figure 28 shows the sample distribution by region, with almost half of the companies concentrating in Bogotá and Cundinamarca region. The rest of the sample results according with Gutiérrez (2010) conclusion that the Colombian metalworking industry is primarily based in the center-west of the country, a region known as the “golden triangle” (a triangle formed by Bogotá, Medellin, and Cali) where most the Colombian population and economic activities are concentrated.

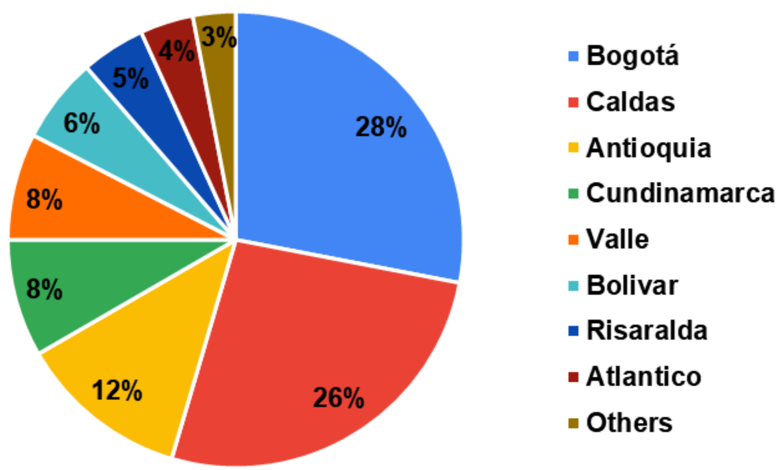

Figure 28. Sample distribution by region

Regarding the different processes performed by the sample companies (Figure 29), more than half of them perform welding, assembly, and machining operations. This is an interest fact, because such processes can be considered end-of-line metalworking processes, which depend on intermediate manufactured products coming from upstream processes such as forming, casting and forging, which represent only about 16% of the sample. Furthermore, all transformation processes require metallic raw materials (mostly steel and iron) which comes from the supply link companies (as presented in Figure 26), but those processes are performed by less than 5% of the sample.

This reveals a structural weakness of the Colombian metalworking chain, which has scarce access to locally produced (or processed) raw materials, as it was previously pointed out by Francica (2008) who stated, regarding the siderurgy sector that “*the sector growth is of great importance for the country’s development because it impacts the added value generation, the production, and the employment. In spite of a reconversion process in the nineties, the grow rate was not sustained*”. In particular, Colombia produces locally only about half of its steel consumption, and most of it consists in reinforced construction bars (76% of the local production), leaving less than 5% of the local production on raw materials for the metalworking industry (Henao and Sarache, 2015). This makes the transformation link of the metalworking chain highly dependent of imported raw materials (Maldonado, 2010), and has penalized its competitiveness, with Orozco and Aguirre (2014) claiming that the metalworking sector has to “face the problem of raw materials scarcity, ensuring the supply and access to raw materials in competitive conditions”.

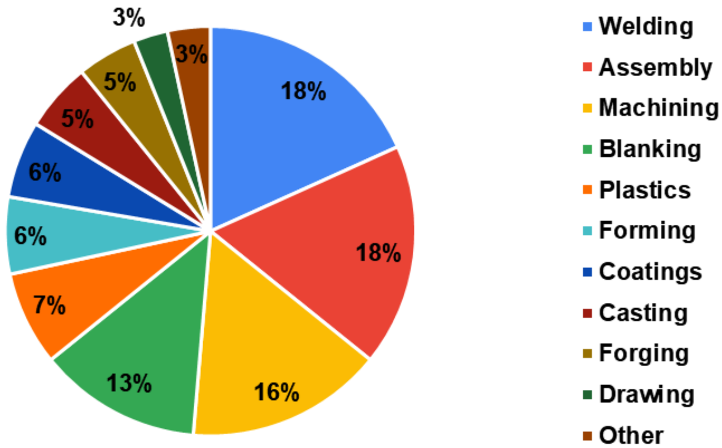

Figure 29. Manufacturing processes performed by the sample companies

As proposed in Section 3.3, and in line with Preciado Hernández et al. (2018), a large portion of Colombian metalworking industries are associated with the automotive industry, which is the case of the sample distribution presented in Figure 30. It is interesting however to notice that two of the sample companies within the “automotive and motion industry” category clarified that their products are directed mainly to the aerospace industry, which is far less developed sector in Colombia, but reaches more sophisticated and competitive markets. The rest of the sample is relatively evenly distributed between metal structures (highly associated with the construction industry), basic metal industries, various metallic products, home appliances, and industrial machinery, which gives a diverse sample of sectors to provide an interesting opportunity to analyze how lean manufacturing practices have reached beyond their initial entry point of the automotive supply chain companies.

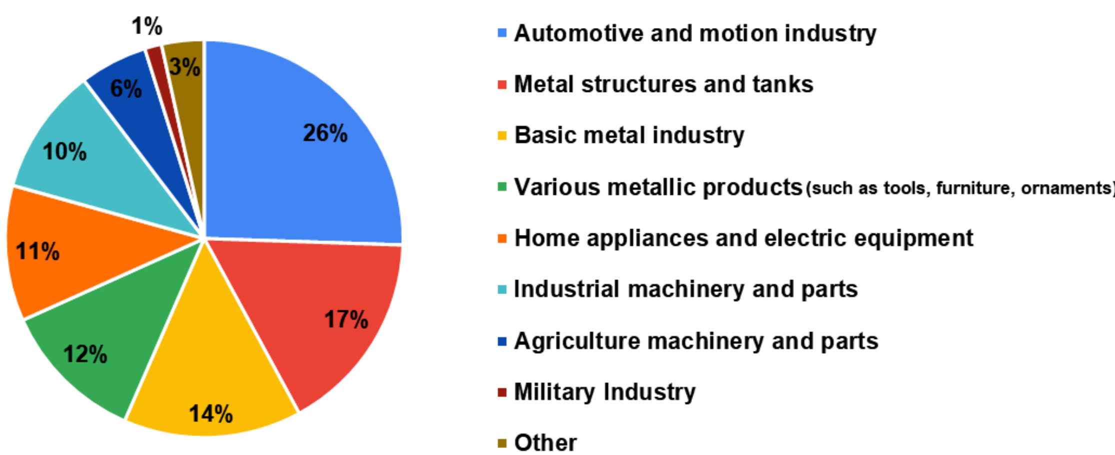

Figure 30. Sample companies’ distribution by products

Figure 31 presents a boxplot of the years since each company started implementing lean manufacturing. In average, the sample companies have been implementing lean manufacturing (or at least some lean practices) for about 4 years, and 75% of them have been in the “lean journey” for six years or less. Only seven companies reported to have been implementing LM for more than 10 years. Only one of said companies is a small company, two have between 51 and 200 employees, one between 201 and 500, and the other 3 have more than 501. It is interesting to notice that only two of those companies are related to the automotive industry, which contrasts with Sanchez (2017) who reported that the first round of the MGC program (the first deployment of lean tools to the Colombian automotive industry supply chain) was completed about 15 years ago..

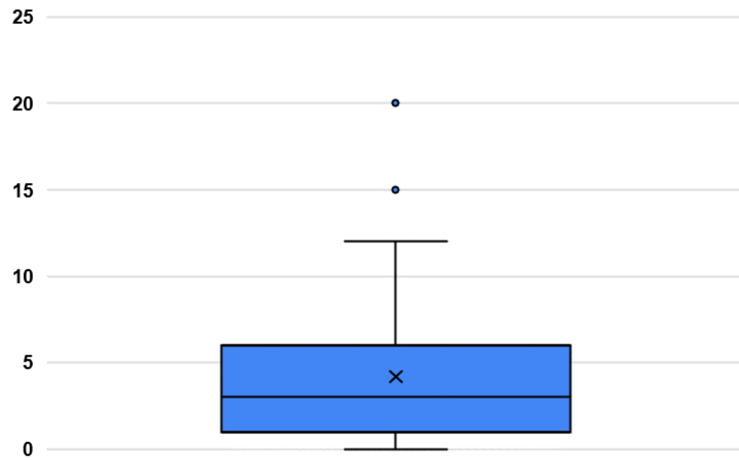

Figure 31. Sample companies’ lean manufacturing implementation time (years)

Another important insight from the data in Figure 31 is that it will probably have an impact in the results regarding lean manufacturing implementation level of the sample companies, and their perceived effects on performance. This because a proper LM implementation can take as long as five years (Burawat, 2019; Čiarnienė and Vienažindienė, 2014), and strong, sustained improvements on performance usually take long to achieve (Sadiq et al., 2021; Susilawati et al., 2015). In fact, a total of 11 companies reported that they have 0 years of lean implementation, which conceptually, should be the equivalent of having no lean level. However, 9 of those companies reported at least a medium level of implementation on at least half of the evaluated lean “bundles”. The other two companies reported “no efforts – no practices implemented” in some of the evaluated items, but not the majority of them.

Therefore, it can be concluded that “zero lean” cases are not present in the sample, in spite of having companies without a formal lean implementation. A reason for this phenomenon is that regardless of having a structured lean program, with interrelated practices being implemented, most companies pursue at least some continuous improvement (and other related) goals. Another possible explanation could be related to language barriers, since not necessarily all respondents have to be familiar with the term “lean manufacturing” (being a Spanish speaking sample), or the improvement programs led by some companies can be implemented under “six-sigma”, “JIT”, or “world class manufacturing” names.

As described in Section 3.3.3, the survey was intended to be completed by managerial positions, especially from those related to the manufacturing operations. Figure 32 shows that this objective was largely fulfilled, with 88% of the respondents being either general managers or managers from manufacturing associated departments. The remaining 12% of the respondents were sales and commercial managers (3%) and other non-managerial company positions (9%), which however stated to have full knowledge of the variables covered in the survey. This can be validated by the last two questions, where each respondent was asked to self-asses their knowledge of lean manufacturing and sustainability. The results in Figure 33 shows that most respondents claimed to have a medium-high knowledge level of LM, while their knowledge level of sustainability is more bell-shaped. This gives a clear indication that through the considered sample, managers perceive more importance to the strategies that provide a clear approach to performance at shop-floor level (and in consequence directly impact operational performance measures), than those that cover a wider TBL approach to performance, therefore, reflecting in less knowledge of sustainability related aspects. It is important however to mention that less than 5% of the respondents claimed to have very low (or none) knowledge of LM and sustainability.

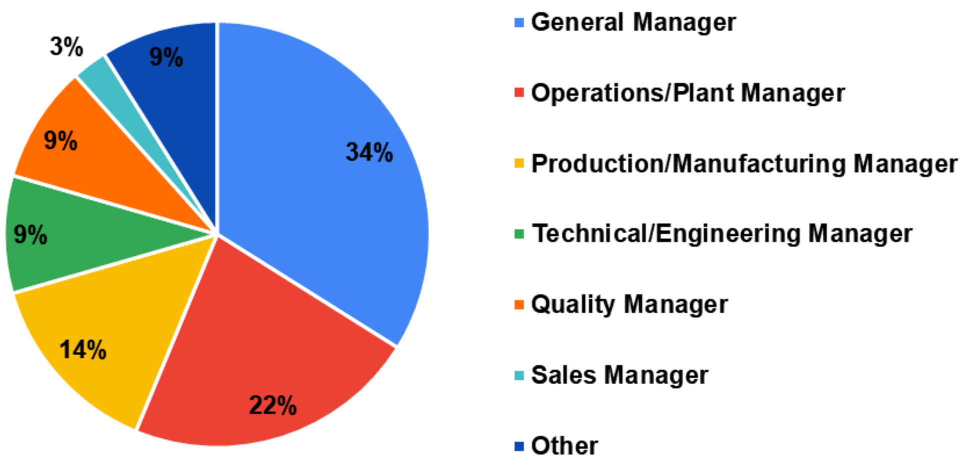

Figure 32. Distribution of respondents by company position

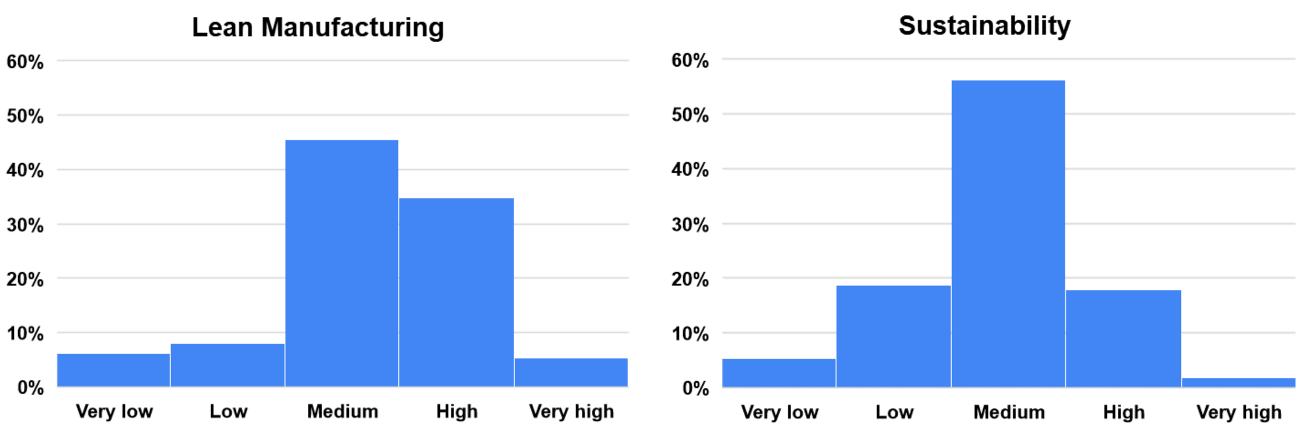

Figure 33. Distribution of respondents LM and Sustainability knowledge level self-assessment

Finally, a last open-question field was included in the questionnaire for comments and suggestions. Less than 20% of the respondents made use of this field, however, some important insights can be extracted from common trends presented in the answers. First, there was several suggestions regarding the need (and the request from the companies) to have academics and Colombian universities more involvement in the deployment of lean trainings and implementation workshops according to the state of the art in the field. One company stated "*this kind of industry urgently requires academic support to implement lean manufacturing to boost continuous improvement and* *economic development, not only of this company, but of the entire country*"[11]. This kind of statement is shared by at least other six companies.

The other common trend in the respondents' remarks relates to the need from the government to incentive companies to invest in continuous improvement and sustainability programs, which allow companies to have some return on their investments via tax refunds, exemptions, or other mechanisms. At least three of the companies share a similar point of view. Regarding this matter, one of the respondents said that "*the government should have research and development centers to support the industry, or, by defect, incentive and help companies to have their own development initiatives*"[12]. Finally, at least six of the companies showed interest in having access to the final results of the research and having more information available about lean manufacturing practices and sustainability.

3.4.1. Lean manufacturing implementation level

The level of lean manufacturing implementation comprises the independent variable of this research. To achieve an idea of said construct, a measurement model based in six first order latent constructs was developed, as show in Figure 21. An additive model for the items comprising each construct was used to aggregate the results presented in the present descriptive results section. This means that the resulting score for each company on each construct comes from the average value of all items reflected by the construct. Since the same 5-point Likert measurement scale was employed on all items, there is no need for results normalization at this point. The complete results (not the aggregated ones here) will be however employed in the structural model presented in subsequent sections.

To render the scale of the histograms presented in Figure 34 more understandable, five 0,8 scale points intervals were defined, thus, the first interval was assigned to "none" (1 to 1,8), meaning an insignificant LM implementation level (according to the proposed scale in the survey), the second represents "low" (1,8 to 2,6), then, "medium" (2,6 to 3,4), "high" (3,4 to 4,2), and finally, "superior" (4,2 to 5). According to this, the complete sample of companies averaged a medium to high level of LM implementation on all six constructs. It is important to notice that the scores in Figure 34 (and Figure 35 in the next section) are aggregated from the complete scale compromising each construct, based on the conclusions from the pilot test. However, it is possible that some of the items will need to be removed from the final scales as a consequence of the measurement model validation described in Section 3.5.

The most highly rated construct corresponds to "Planning and processes", where 33% of the companies reported a superior level of LM implementation, and 39% a high one. This could be explained because the practices that comprise this construct (i.e., lot size reduction, continuous flow, flexible planning, and WIP reduction) are also common to other methodologies and strategies such as JIT, six sigma, and agile manufacturing. Therefore, even a company does not have a proper lean manufacturing program in place, it is highly possible that it will be nevertheless making efforts on those fronts. This is also a similar case for the quality construct (55% of the companies are in the high-superior level) and the supply construct (57% of companies in high-superior level), where it also

[11]Taken from the survey suggestions of a medium automotive industry company located in the city of Bogotá.
[12]Taken from the survey suggestions of a small automotive industry company located in the city of Bogotá.

applies that regardless of the company doing a concrete lean effort, it is likely that they will be doing sound efforts to improve those dimensions.

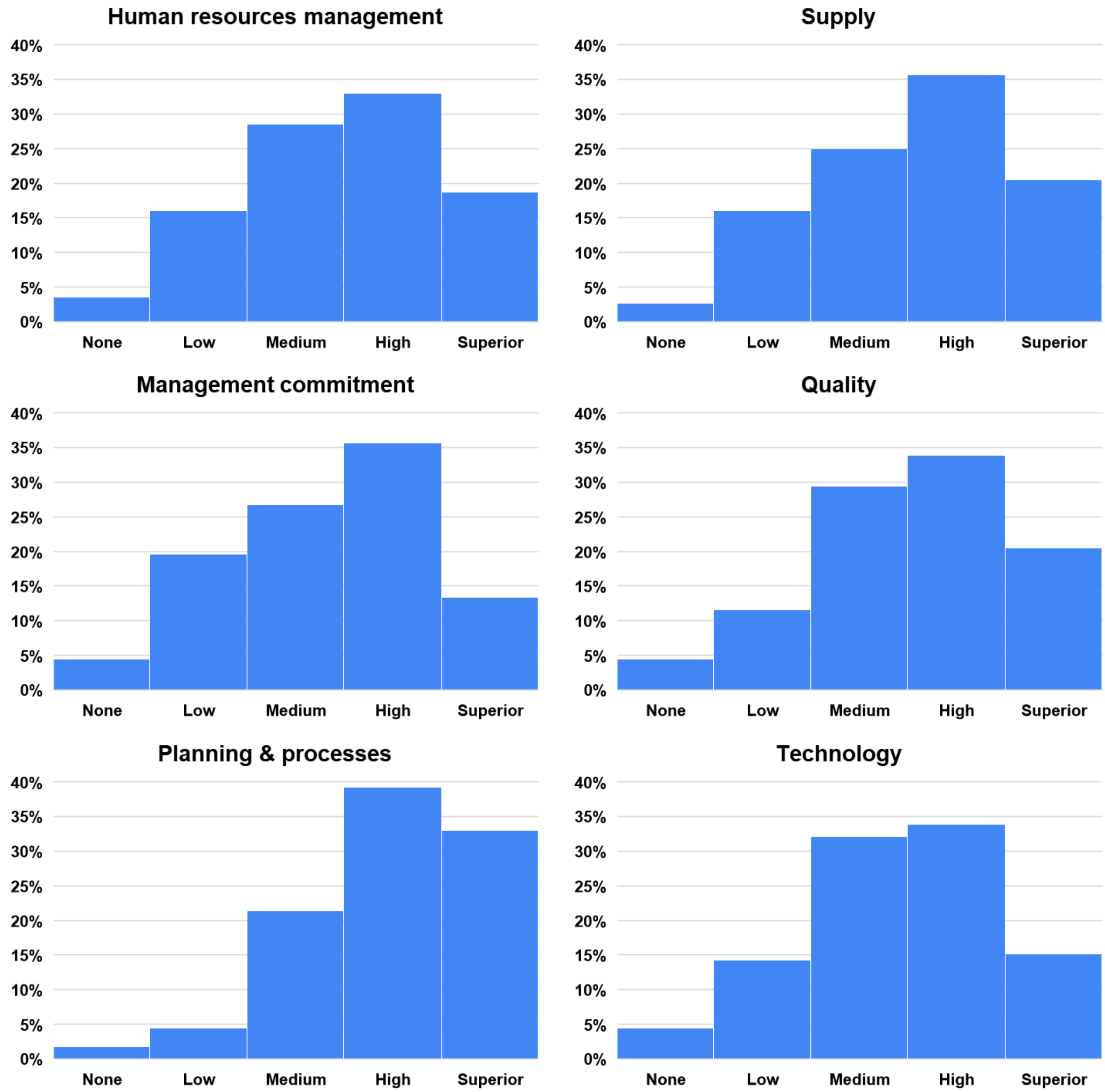

Figure 34. Lean manufacturing first order constructs aggregated results

In the case of management commitment, 36% of the companies fell in the high level, but more than half of them have a medium to low level of implementation. The survey items comprising this construct are specifically directed towards the management commitment and support to the lean efforts, therefore, it was expected that not all companies had such a clear strategic direction towards this construct. Finally, for the technology and HRM constructs, the companies' levels are more balanced towards the medium-high level, with companies more widespread across all five levels of implementation. This points to a lower interest on those dimensions, which can be explained by the "hard" nature of lean practices in the technology construct, which usually require more expensive levels of investment to implement. Also, given that many of the lean practices are subject to cultural and context factors (Henao et al., 2019), in particular those related to HRM, higher levels of adaptation are required to achieve the desired effectiveness of said practices, as previously concluded on the results of the case study (Section 3.2.2) and exposed on Table 26, which could also explain the none to medium level of almost half of the companies.

It can be said that the sample of Colombian metalworking companies have in average a medium to high level of lean manufacturing implementation, which results interesting when contrasting it with the data of Figure 31 which shows that most companies have been implementing lean for six years or less, which means that either many companies are achieving a lean maturity level, which comes after four to five years of a committed implementation of lean (Čiarnienė and Vienažindienė, 2014) or the predominant countrywide lean deployment approach through the automotive supply chain helped companies to implement lean in a more proven and straightforward way (derived from the lessons learned by the automotive companies in their lean programs at corporate level worldwide) which managed to achieve higher levels of implementation in shorter times. Nevertheless, the general distribution of data closely match a normal distribution, which is important for the predictive power of later analysis (effect of LM implementation on sustainable performance) since there are companies distributed along the whole spectrum of levels of LM implementation, therefore, it will be possible to statistically correlate if those on one side of the LM spectrum correlate to those on the same side of the sustainable performance spectrum (i.e., a high level of LM implementation leads to a high level of sustainable performance).

3.4.2. Sustainable performance

Analog to the aggregated score for lean manufacturing presented in the previous section, and additive model for each dimension of sustainability was employed to assess the overall sample scores in the independent variable (sustainable performance). Sustainable performance is represented by a second order latent construct, comprised by three first order latent constructs (one for each TBL pillar), as exposed in Figure 23. The histograms in Figure 35 use the same numerical intervals of those on Figure 34, but the descriptive scales match those of the survey for this variable. Therefore, an average value from 1 to 1,8 on the items from each dimension is considered a "significant detriment" to the performance on said dimension, then, 1,8 to 2,6 means "detriment", 2,6 to 3,4 represents "no change", 3,4 to 4,2 reflects an "improvement" and finally, 4,2 to 5 means a "significant improvement" on performance.

As Figure 35 reveals, most of the companies (64%) claimed to have obtained some level of operational performance improvement as a result of the implementation of lean manufacturing. This was an expected result as there is a breadth of literature concluding that LM has a positive effect on most operational performance variables. However, it is not neglectable the number of companies that perceived insignificant or no changes at all (32%), which results contrasting with the level of LM implementation of most of the sample companies. However, there could be two possible explanations for this phenomenon. First, more than half of the companies have been implementing lean practices for less than five years (Figure 31), which according to some authors can be a short time to fully perceive the expected benefits from lean (Abolhassani et al., 2016; Čiarnienė and Vienažindienė, 2014; Zhou, 2016) and they are at risk of returning to the old, previous-lean, way of doing things (Dombrowski and Mielke, 2013; Grigg et al., 2020).

The second explanation could be extracted from the results of the case study performed on this research, described in Section 3.2.2. As it was previously mentioned, many companies implement specific lean practices because they are a requisite from some of their customers, which intend to have a standardized supply and quality management system across they key suppliers. This is often the case of some of the sample companies since they belong to the automotive industry, where lean practices were transferred to them by the assembly plants. This creates the risk of having to implement lean practices not because of a particular commitment of the company management and workforce to the lean principles, but just as a customer requirement. Said “purposeless” approach could lead to a merely superficial lean adoption, which in the end, does not render any significant performance improvements.

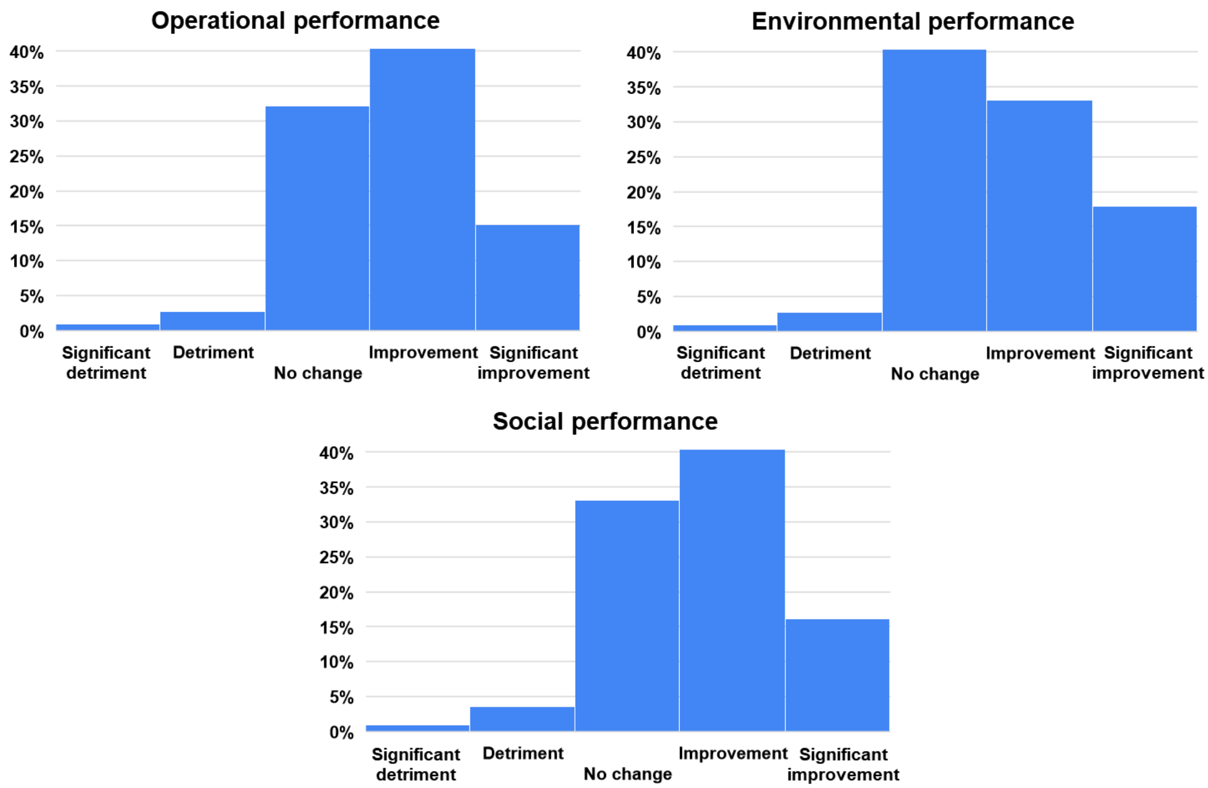

Figure 35. Sustainable performance first order constructs aggregated results

This is supported by a common trend in claims from the case study company at all the studied levels. One member from the company’s management stated “*some lean initiatives have been applied by some company areas, but it has been difficult to achieve the whole company support to implement a coordinated LM system that is included in the long-term organizational strategy*”[13]. At the tactic team level, where most of the persons given the task to implement the lean practices at plat-floor level belong, this questioning of the meaning behind the lean program was more widespread, with comments such as “*sometimes we have tried to implement practices without fully understanding the objective of them*”, and “*most of the lean tools that we have point to one of the goals (i.e. lean goals presented in this research), but only until now we are beginning to understand why we are doing it*”[14]. When trying to understand why the participants had those point of view, the whole group concluded that there was not a coordinated lean effort in place, but just the implementation of a series of practices that were required by some of their customers to meet their quality management assessments, which in the end, were perceived as “paperwork” and not as a meaningful continuous

[13] Translation from the remarks of one management-level employee of the case study company.
[14] Translation from the remarks of some tactic-level employees of the case study company.

improvement system. Finally, there was also evidence at the operator's level, with comments such as "*sometimes we are called up to trainings where they explain to us that we have to change some things, but they don't tell us why. If you know why you are doing something it is easier to do it*"[15].

Regarding environmental performance, the scale with the largest portion of companies corresponded to "no change" (46%), followed by "improvement" (33%). Since no correlation study between the measured variables has been performed at this point, it is not possible to conclude if the lack of significant changes in environmental performance is somehow related to the level of lean manufacturing implementation. However, it is important to mention that in light of the results of previous research, many companies see environmental benefits not as a direct effect of LM, but as a "byproduct" derived from some of the practices (Piercy and Rich, 2015; Resta et al., 2016), and given the relatively short time of lean implementation of many of the sample companies, those environmental benefits have been not perceived yet.

On the other hand, as Dieste et al. (2020) point out "*the impact of lean practices on the environment is still unclear*", a notion which has been previously supported by other authors (Bergenwall et al., 2012; Galeazzo et al., 2014; Resta et al., 2017). Therefore, there is not enough empirical support to expect that in a sample of companies with a medium to high level of lean implementation, most of them tend to perceive significant improvements in their environmental performance. It is worth mentioning however that, from all the companies, regardless of the causes, less than 5% perceived a detriment of their environmental performance since implementing LM.

Finally, the results of social performance on the sample companies are interesting since most of them perceived an improvement since the adoption of lean (46% improvement, 16% significant improvement). Again, as there is no correlational study at this time, it is not possible to conclude that this improvement is statistically related to the level of lean manufacturing implementation. However, as literature relating LM to social performance is relatively scarce (Besiou and Van Wassenhove, 2015; Resta et al., 2017) any result could be expected, and few theoretical grounds are available to interpret them. A likely explanation could be that many lean practices, and especially those related to HRM (on which the majority of sample companies were found to have a high to superior implementation level) aim to develop people skills through empowerment, training, brainstorming, and continuous improvement, which could give a high sense of meaning to an individual contribution to the organization, improving motivation and welfare (Brito et al., 2019; Burawat, 2019; Tyagi et al., 2021), therefore, favoring some social performance indicators at the workforce level (Henao et al., 2021).

It is also possible that the companies did indeed perceived an improvement in many social performance indicators but lacked the ability to discern the cause of such improvements and mistakenly attributed them to the implementation of lean practices or other strategies that they were implementing in recent years. This could be argued because in recent years there has increasing pressure on companies to be compliant with work regulations, that in turn have become more strict in the last years in order to comply with free trade agreements that the Colombian government has signed with several developed countries, such as USA (2011), South Korea (2016), or the European Union (2012) (Bartels, 2013; Harrison et al., 2019). Said agreements provide that, in order to have a

[15] Translation from the remarks of one operator-level employee of the case study company.

fair market competition between the signatories, labor standards have to be improved by Colombian companies to proportionally match those of the other signing parties, and that government institutions must incentive and enforce the compliance of said standards (Orjuela-Castro et al., 2019; Ramirez-Contreras and Faaij, 2018).

3.5. Measurement model validation

Through the pilot test performed in Section 3.2.3, a confirmatory factor analysis was performed to give an indication that the constructs structure proposed on the measurement model derived from theory, were indeed a good fit for the initial data collected through the pilot survey. The results obtained indicated that the proposed model was indeed coherent with the data, therefore giving grounds to continue with the full-scale survey distribution through the complete sample. At this point the recovered data must be definitively tested to prove the validity and reliability of the sample's dataset. The resulting validation of the measurement model will provide the input on the subsequent structural model under statistically valid assumptions that the employed factors are indeed a representation of the underlying constructs on the dataset (Hair et al., 2009), and are suitable for a cause-effect analysis.

3.5.1. Principal components analysis

As it was stated in previous sections, the survey instrument was purposely designed for the present research from constructs derived from state-of-the-art literature, in order to collect primary data. Therefore, as opposed to the use of secondary data, which usually requires an exploratory factors analysis (to check how the available items can be grouped together into constructs), the pursued approach will be one of confirmatory factor analysis, where the collected data is statistically confirmed to adequately fit in the theoretical constructs.

These assumptions will require however to perform a series of statistical tests that confirm that the dataset is suitable for factorization (i.e., to be grouped into different constructs), and that the set of constructs explain a large portion of the overall variance of the model, or in other words, that the items conforming each construct explain a significant larger part of the factor variance than what can be explained by external variables or errors. Said assumptions can be proven through a sample adequacy test (Prasad et al., 2016) and therefore by performing a principal component analysis (PCA).

To check the sample adequacy (i.e. that the data is suitable for factor reduction) two tests were performed. First the Kaiser-Meyer-Olkin (KMO) test indicates the proportion of variance of the items that can be caused by underlying factors, or, in other words, a value of 1 would indicate that all the variance of the measured variables can be a result of the factors variances (IBM, 2020; Massey, 2019). Table 33 and Table 34 present the KMO measures obtained from IBM SPSS for both the items comprising the lean manufacturing construct and those of the sustainable performance construct. The results of 0,886 (for LM items) and 0,861 (for sustainable performance items) indicate that the sampling is highly adequate and is well above the 0,5 threshold commonly used by other authors in the same field (Moyano-Fuentes et al., 2019; Prasad et al., 2016; Sunder and Prashar, 2020). The second adequacy test performed was the Bartlett's test of sphericity, which tests the null hypothesis that the correlation matrix is an identity matrix (UCLA, 2021), therefore, indicating that there is no redundancy between variables that can be interpreted by some factors. The resulting significance presented in Table 33 and Table 34 ($p<0,001$) means that for the dataset the Bartlett's test is highly significant so the null hypothesis can be rejected, and the data can be considered appropriate for factor analysis (Field, 2013).

Table 33. KMO and Bartlett's tests for sample adequacy of lean manufacturing items

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,886
Bartlett's Test of Sphericity	Approx. Chi-Square	1613,33
	df	276
	Sig.	,000

Table 34. KMO and Bartlett's tests for sample adequacy of sustainable performance items

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,861
Bartlett's Test of Sphericity	Approx. Chi-Square	757,47
	df	120
	Sig.	,000

After ensuring that the data is suitable for factorization, the PCA allows to identify how much of the total model variance can be explained by the underlying factors. Table 35 and Table 36 presents the eigenvalues for the specified number of factors on each measurement model, along with the correspondent percentage of variance explained by each underlying factor, before (left of the table) and after rotation (right). On both cases an orthogonal varimax rotation (with Kaiser normalization) was employed to maximize the eigenvalue load on each extracted factor and redistribute the variance among the resulting constructs (Marodin et al., 2019). It is important to notice that since the variables are standardized (the PCA analysis is performed on the correlation matrix), the total variance of the model equals the number of items (each variable variance is 1) (UCLA, 2021), therefore the total variance explained by the extracted factors remains the same for the rotated and non-rotated solutions, but the variance explained by each factor is more uniformly distributed on the rotated solution, and in consequence, factor loadings for each item become generally higher.

Table 35. Factor extraction eigenvalues and variance for lean manufacturing construct

Component	Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	10,320	43,002	43,002	3,096	12,900	12,900
2	1,812	7,551	50,553	3,095	12,895	25,795
3	1,477	6,153	56,706	3,043	12,678	38,473
4	1,283	5,346	62,052	3,019	12,581	51,054
5	1,012	4,217	66,268	2,748	11,450	62,504
6	0,942	3,924	70,192	1,845	7,688	70,192

Table 36. Factor extraction eigenvalues and variance for sustainable performance construct

Component	Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6,191	38,695	38,695	3,669	22,932	22,932
2	1,663	10,394	49,088	2,905	18,155	41,087
3	1,435	8,967	58,055	2,715	16,968	58,055

The results of both the lean manufacturing construct and the sustainable performance construct (Table 35 and Table 36) show that the factors explain a large enough amount of the total variance (70,2% for LM and 58,1% for sustainable performance), therefore indicating that the number of factors is suitable enough for a subsequent cause-effect analysis among the resulting constructs without significant loss of information (Schneider and Arminger, 2007). It is important to mention that in the sustainable performance construct, all three factors presented eigenvalues above 1 in both the non-rotated and rotated solutions, which results consequent with the Kaiser criterion (Vargas-Halabí et al., 2017).

In the case of the lean manufacturing constructs, only five factors present eigenvalues above 1 for the non-rotated solution, which means that the sixth factor does not meet the Kaiser criterion on the initial solution. However, there are several arguments justifying maintaining all six factors. First, on the rotated solution the eigenvalues are more evenly distributed on the factors resulting in all of them having values above 1, and as for the non-rotated solution, the sixth factor has nevertheless an eigenvalue of 0,942 which results close enough to 1 in order to explain a sufficiently large portion of the total variance (Schneider and Arminger, 2007). Second, since the selected approach follows a CFA instead of an EFA, the number of factors was previously derived from theoretical bases, therefore, if the subsequent CFA for the measurement model produces an adequate fit the model can be considered consistent with theory. Finally, the Kaiser criterion accuracy depends on a series of factors which consider the number of factors, the average communalities after extraction (above 0,7), and more importantly, the sample size (above 250), which is larger than the sample size for the present research, and therefore, renders the Kaiser criterion less accurate in this case (Braeken and van Assen, 2017; Field, 2013).

Finally, Table 37 and Table 38 present the communalities for each case. Under the assumption that all variance is common for the model and since the correlation matrix is used for the PCA, the initial communalities for each item equals 1, as shown on both tables. However, after extraction the right column of the table presents the common variance of the data structure for the resulting number of factors. In the words of Field (2013), "*after extraction some of the factors are discarded and so some information is lost. The amount of variance in each variable that can be explained by the retained factors is represented by the communalities after extraction*".

Table 37. Communalities for the lean manufacturing items

Item	Initial	Extraction
HRM1	1,000	,599
HRM2	1,000	,665
HRM3	1,000	,697
HRM4	1,000	,677
MGM1	1,000	,672
MGM2	1,000	,640
MGM3	1,000	,699
MGM4	1,000	,725
PAP1	1,000	,547
PAP2	1,000	,655
PAP3	1,000	,778
PAP4	1,000	,720
SUP1	1,000	,675
SUP2	1,000	,788
SUP3	1,000	,746
SUP4	1,000	,666
QTL1	1,000	,615
QTL2	1,000	,774
QTL3	1,000	,833
QTL4	1,000	,795
TEC1	1,000	,781
TEC2	1,000	,675
TEC3	1,000	,720
TEC4	1,000	,704

The resulting communalities range from 0,547 to 0,833 on the lean manufacturing construct (Table 37) which represents a very good proportion of variance for each factor, allowing to ensure the accuracy of the parameter estimates (factor loadings and regression weights) both in the measurement model, and in the subsequent structural model (Wolf et al., 2013). In the case of the sustainable performance construct, communalities are above 0,49 in all cases (Table 38), which is in the range of the values proposed by Curran et al. (2003), except from one item on each construct (OPR3: 0,415; ENV4: 0,468; SOC4: 0,334), and that are however above the levels considered in (UCLA, 2021). The values of the communalities will result helpful during the CFA (in Section 3.5.3) since items with low communalities can point to variables that are not well represented in the common factor space, and therefore can be removed in alternative measurement models to check for improvements in the model fit indices.

Table 38. Communalities for the sustainable performance items

Item	Initial	Extraction
OPR1	1,000	,571
OPR2	1,000	,568
OPR3	1,000	,415
OPR4	1,000	,512
OPR5	1,000	,672
OPR6	1,000	,591
ENV1	1,000	,685
ENV2	1,000	,715
ENV3	1,000	,686
ENV4	1,000	,468
ENV5	1,000	,641
SOC1	1,000	,709
SOC2	1,000	,499
SOC3	1,000	,496
SOC4	1,000	,334
SOC5	1,000	,725

3.5.2. Internal consistency

In order to test internal consistency, the most common method is to perform a Cronbach α analysis (Tsang et al., 2017). This gives an idea of how much different items measuring the same construct are consistent among them, or, in other words, point to the same direction (Wanzer et al., 2019). Several authors use a threshold of Cronbach α values above 0,6 or 0,7 to consider the survey data as “reliable” (Kim et al., 2020; Marodin et al., 2019; Tortorella and Fettermann, 2018), especially for newly developed questionnaires or early stages of research (Moyano-Fuentes et al., 2019).

Although each construct Cronbach α was calculated at the pilot test stage obtaining satisfactory values, it is important to mention that Cronbach α is a property related to a specific dataset, therefore, it is not used to estimate the reliability of the questionnaire (i.e., the set of questions that comprise the survey), but to give an estimate of the reliability of the group of answers obtained (Tsang et al., 2017). Therefore, it is required to be estimated at this stage for the complete dataset. The Cronbach α calculation was performed using SPSS for each construct and presented in Table 39. Also, the resulting value for each construct if a given item is deleted from the scale is reported.

Considering the values reported on Table 39, and according to the classification proposed by Tyagi et al. (2021), at the bottom of the same table, all constructs present at least “good” Cronbach α values, except for HRM, MGM, and SOC, which, however, can be considered “satisfactory”. In addition, only in three constructs the Cronbach α value presented improvements if items were deleted from the scale (QLT, ENV, and SOC). However, the improvements result neglectable considering that α values with the complete scale are already good in such cases, and there is the risk of losing valuable information if said items are deleted.

The obtained results proved the internal consistency and reliability of the dataset obtained from the sample companies, further indicating that the proposed factorization (the items proposed for each construct derived from state-of-the-art-literature) presents a good match between the theoretical conceptualization of the selected variables and the real-world results collected trough the survey.

Table 39. Cronbach α values for each construct

Variable	Construct	Cronbach α	Item	Cronbach α if item deleted
LEAN MANUFACTURING	HRM	0,774	HRM1	0,716
			HRM2	0,725
			HRM3	0,655
			HRM4	0,772
	MGM	0,796	MGM1	0,773
			MGM2	0,721
			MGM3	0,742
			MGM4	0,736
	PAP	0,813	PAP1	0,770
			PAP2	0,786
			PAP3	0,770
			PAP4	0,730
	SUP	0,828	SUP1	0,794
			SUP2	0,744
			SUP3	0,769
			SUP4	0,823
	QLT	0,818	QLT1	0,838
			QLT2	0,748
			QLT3	0,746
			QLT4	0,739
	TEC	0,804	TEC1	0,756
			TEC2	0,734
			TEC3	0,764
			TEC4	0,765
SUSTAINABLE PERFORMANCE	OPR	0,838	OPR1	0,803
			OPR2	0,810
			OPR3	0,830
			OPR4	0,823
			OPR5	0,797
			OPR6	0,807
	ENV	0,832	ENV1	0,778
			ENV2	0,773
			ENV3	0,803
			ENV4	0,839
			ENV5	0,793
	SOC	0,748	SOC1	0,673
			SOC2	0,745
			SOC3	0,664
			SOC4	0,767
			SOC5	0,663
Cronbach α proposed intervals from Tyagi et al. (2021): α>0,9: outstanding; α>0,8: good; α>0,7: satisfactory; α>0,6: questionable				

3.5.3. Confirmatory factor analysis

After confirming that the data is suitable for factorization (Section 3.5.1) and that the items comprising each construct show internal consistency (Section 3.5.2), a confirmatory factor analysis was performed. As it has been previously stated through this document, the CFA approach results useful when the proposed measurement model has a theoretically sound base structure, and the researcher wants to confirm that the examined dataset indeed fits said a-priori defined measurement model (Nawanir et al., 2018; Varela et al., 2019). A set of underlying assumptions about the data are needed to perform CFA, with the most important of them being that all indicator variables must exhibit multivariate normal distributions (Bagozzi and Yi, 2012; Davcik, 2014; Yuan and Kano, 2018).

However, the assumption of multivariate normality is not generally met (or at least proven), with evidence from Shook et al. (2004) noting that at least 80% of studies in strategic management research using SEM did not specified their sample distribution, a similar conclusion to that obtained by Andreassen et al. (2006) while evaluating marketing research studies. One given explanation is that, while in large random samples derived from the observations of physical phenomenon's (for example, a chemical reaction test on a laboratory environment) normally distributed data can be easily expected, in relatively small, real world observations derived from human behavior and perceptions (as it is the case of management research) the normality of data distribution is highly difficult to achieve, let alone, the achievement of multivariate normality for a series of items (Bono et al., 2017; Gao et al., 2008).

Normality of data can be analyzed by measuring kurtosis and skewness (Abu et al., 2019), while multivariate normality can be assessed by means of the multivariate kurtosis or Mardia test (Gao et al., 2008). For these purposes, the kurtosis and skewness values of each item were calculated using AMOS "Tests for normality and outliers" function, with results reported in Table 40 and Table 41 for the lean manufacturing items and the sustainable performance items respectively. It is important to mention that SPSS (and in consequence AMOS) subtracts 3 from the fourth central standardized moment (i.e., the "original" kurtosis value), therefore having a kurtosis value of 0 for a perfect normal distribution. According to Hair et al. (2009) and Watson (2019), a normal distribution can be expected if skewness falls between -2 and +2, and kurtosis falls between -7 and +7. In addition, values of multivariate kurtosis above 7 point to multivariate non-normality (Curran et al., 2003).

As Table 40 and Table 41 indicate, all variables in the data set exhibit close to normal distributions according to their skewness and kurtosis values. However, regarding the multivariate normality assumption required for SEM analysis, the lean manufacturing items present a value of 111 for multivariate kurtosis, while the sustainable performance items value is 59, both of them above the commonly used thresholds. This indicates that the data set retrieved from the sample companies does not meet the assumptions of multivariate normality, which was however expected given the sample size and the studied phenomenon (Bono et al., 2017).

The non-normal multivariate distribution of the data is nevertheless a problem that can be managed if a proper handling of the data, analysis, and interpretations is performed. Andreassen et al. (2006) suggest that the researcher can deal with the non-normality in four possible ways, including the use of the Satorra-Bentler correction. This method is also commonly known as "robust estimation" and is often used in SEM (Kim et al., 2020; Leguízamo-Díaz and Moreno-Mantilla, 2014; Rhemtulla et al., 2012). However, this method is still sensitive to sample size when dealing with reflective constructs (Andreassen et al., 2006; Davcik, 2014), and it is not explicitly provided by AMOS.

Table 40. Multivariate normality test for lean manufacturing items

Variable	skew	c.r.	kurtosis	c.r.
TEC1	-0,575	-2,505	0,127	0,276
TEC2	-0,084	-0,367	-0,682	-1,487
TEC3	-0,304	-1,323	-0,192	-0,418
TEC4	-0,301	-1,312	-0,838	-1,825
QLT1	-0,496	-2,163	-0,209	-0,455
QLT2	0,129	0,560	-0,867	-1,890
QLT3	-0,340	-1,480	-0,750	-1,634
QLT4	-0,597	-2,602	0,101	0,219
SUP1	-0,154	-0,671	-0,616	-1,342
SUP2	-0,636	-2,771	0,075	0,164
SUP3	-0,667	-2,907	-0,052	-0,113
SUP4	-0,045	-0,197	-0,824	-1,795
PAP1	-0,468	-2,042	0,080	0,174
PAP2	-0,875	-3,815	1,153	2,513
PAP3	-1,054	-4,596	1,274	2,776
PAP4	-0,723	-3,151	0,315	0,686
MGM1	-0,620	-2,703	0,717	1,563
MGM2	-0,151	-0,658	-0,847	-1,846
MGM3	-0,115	-0,501	-0,763	-1,663
MGM4	-0,152	-0,661	-0,836	-1,823
HRM1	-0,300	-1,306	-0,209	-0,455
HRM2	-0,160	-0,697	-0,545	-1,188
HRM3	-0,327	-1,425	-0,599	-1,305
HRM4	-0,335	-1,459	-0,506	-1,103
Multivariate			111,120	16,792

Table 41. Multivariate normality test for sustainable performance items

Variable	skew	c.r.	kurtosis	c.r.
OPR1	-0,140	-0,700	-0,348	-0,868
OPR2	-0,440	-2,191	0,129	0,322
OPR3	-0,314	-1,563	-0,134	-0,333
OPR4	-0,300	-1,495	-0,097	-0,241
OPR5	-0,379	-1,889	0,225	0,561
OPR6	-0,343	-1,709	0,025	0,062
ENV1	-0,192	-0,956	-0,138	-0,345
ENV2	-0,243	-1,213	0,305	0,760
ENV3	-0,204	-1,018	-0,348	-0,867
ENV4	-0,298	-1,484	0,629	1,566
ENV5	-0,124	-0,618	-0,403	-1,004
SOC1	-0,144	-0,716	0,232	0,579
SOC2	-0,090	-0,450	-0,194	-0,482
SOC3	-0,032	-0,159	-0,385	-0,960
SOC4	-0,353	-1,759	-0,643	-1,601
SOC5	-0,475	-2,365	0,568	1,415
Multivariate			58,955	14,992

However, other robust estimation methods alternative to the Satorra-Bentler correction are available (Shook et al., 2004). In particular, IBM (2018) states that "*Amos does not provide the Satorra-Bentler scaled Chi-square. Instead, Amos provides bootstrapping for situations where the assumptions underlying maximum likelihood chi-squares and standard errors may be violated. In fact, for large samples, both Amos and the Satorra-Bentler scaled Chi-square have the same p-value. Some simulation results show that bootstrapping is even better than the Satorra-Bentler scaled Chi-square*". Along this line, the present research will follow the bootstrapping approach with the Bollen-Stine procedure as proposed by Crowson (2019) and Kim and Millsap (2014) to deal with the distributional and sample size assumptions.

In the words of Corrêa Ferraz (2020), "*bootstrap provides an alternative elegant solution to the problem of approximating the sampling distribution of a statistic when the population distribution is unknown. Bootstrapping draws repeated samples with replacement (called bootstrap samples) from the parent sample; the parameter of interest is then determined for each bootstrap sample and the empirical distribution of each parameter's bootstrap may be used for statistical inference*". AMOS uses the Bollen-Stine (BS) approach to bootstrap significance values of the chi-square statistic, therefore, providing a corrected p-value for the model's χ^2.

In line with Crowson (2019), 2000 bootstrap samples were generated for each CFA model (the lean manufacturing construct, and the sustainable performance construct), and the "Bootstrap ML" and "Bollen-Stine bootstrap" options were selected in AMOS. The complete measurement models were analyzed in both cases. The parameter estimates for the complete (all items) lean manufacturing measurement model are reported in Figure 36. However, as Table 42 shows, the complete model does not present an acceptable fit by all employed indices, and, especially, by testing the "null hypothesis" under the BS bootstrap (ho: the model is correct), which returns a p-value of 0,023, therefore providing grounds to reject the null hypothesis ($p<0,05$).

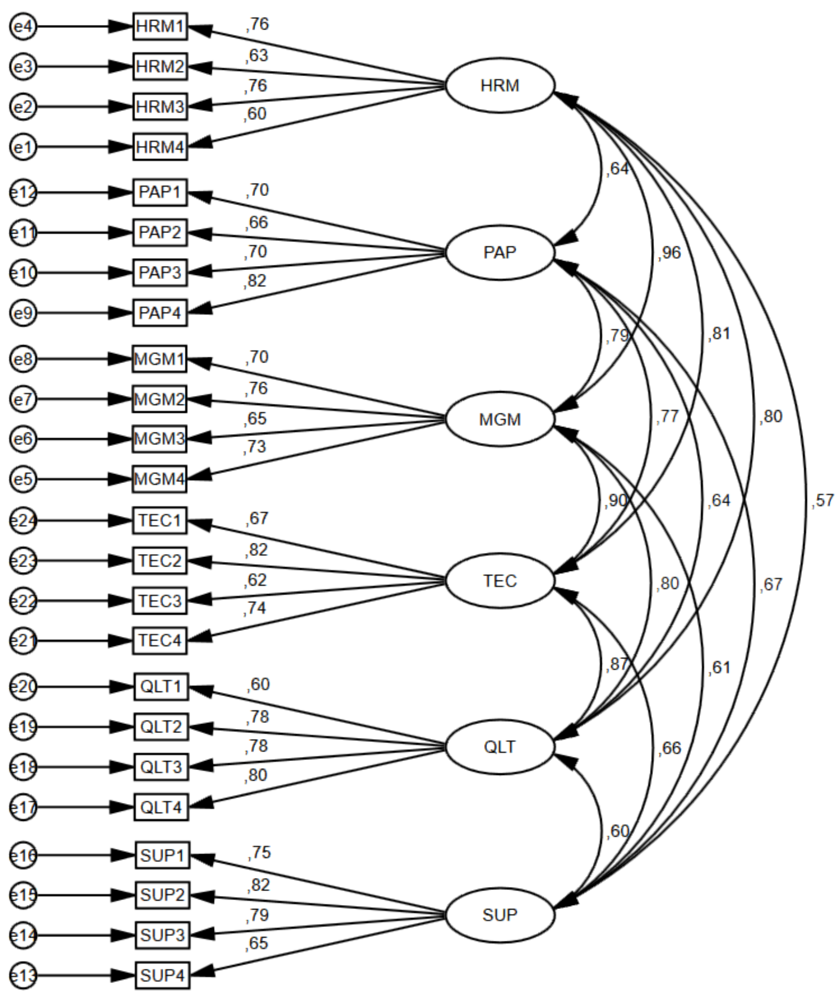

Figure 36. Original lean manufacturing measurement model estimates

To improve model fit, the sample's correlation matrix was examined for items presenting low inter-construct correlations (a sign of poor convergent validity) and high intra-construct correlations (a sign of poor discriminant validity), which in turn reflected in poor factor loadings. In order to preserve as much information as possible from the original data set, items presenting the abovementioned conditions were eliminated from the measurement model one at the time, and the fit indices compared for improvement. The process was performed in several iterations, until the fit improvement became marginal.

The final lean manufacturing measurement model is presented in Figure 37, along with its corresponding standardized parameter estimates (factor loadings and construct correlations). As the data in Table 42 shows, the selected model corresponds to Model 5. Although Model 6 presents acceptable fit indices and can be also considered valid under the Bollen-Stine bootstrap value (which provides evidence to accept the null hypothesis, that the model is correct), with Model 5 BSp=0,074>*0,05* and Model 6 BSp=0,101>*0,05*, Model 5 is considered a better fit as it retains more information of the original dataset without a significant increase in its χ^2 statistic. In other words, the decrease in χ^2 from Model 5 to Model 6 is not significant compared to the decrease in the degrees of freedom (Arbuckle, 2014).

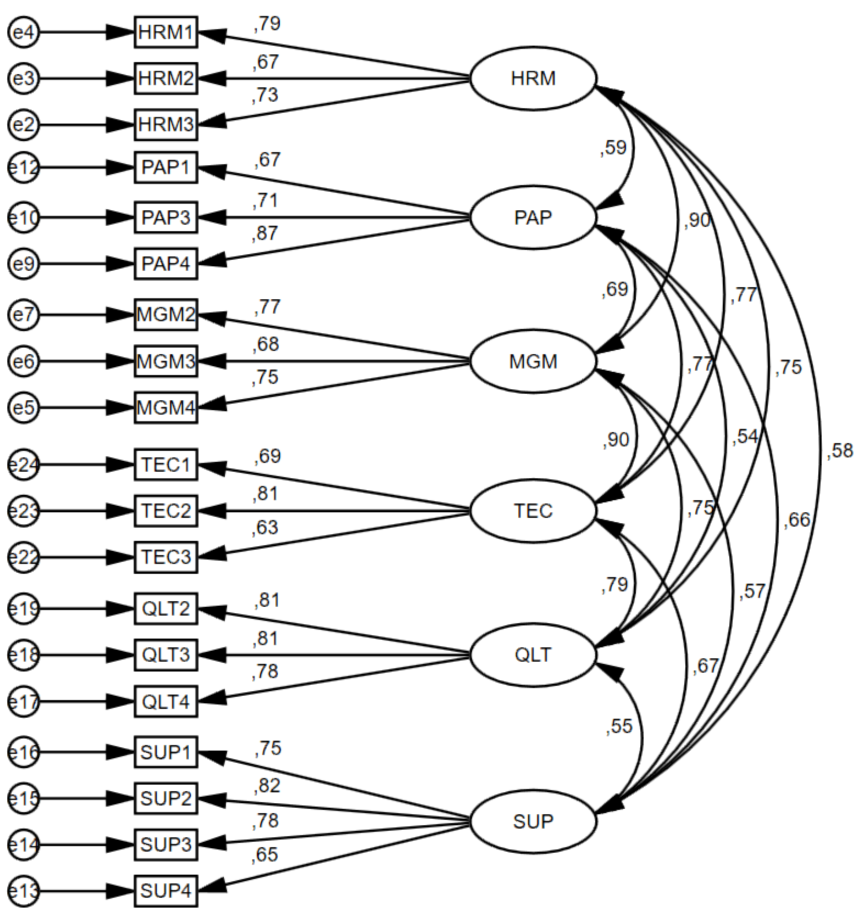

Figure 37. Final lean manufacturing measurement model estimates

Model 5 has a χ^2 statistic of 235,225 and 136 degrees of freedom (df), while Model 6 χ^2 is 196,995 with 119 degrees of freedom. According to Arbuckle (2014) two models can be compared by analyzing their difference in χ^2 with respect to their difference in df. The χ^2 difference between both models is 38,27 with 17 df of difference. The significance level of a χ^2 value of 38,27 with 17 df is p=0,0022<*0,05*, therefore the χ^2 difference is not significant, supporting the fact that Model 5 presents a better fit.

Table 42. Lean manufacturing measurement model fit indices

Model number	Deleted Items	χ^2	df	Bollen-Stine p	χ^2/df	CFI	PNFI	RMSEA
1	None	477,201	237	0,023	2,014	0,841	0,629	0,095
2	HRM4	428,524	215	0,021	1,993	0,852	0,635	0,094
3	HRM4, QLT1	375,351	194	0,029	1,935	0,868	0,643	0,091
4	HRM4, QLT1, MGM1, TEC4	284,701	155	0,071	1,837	0,890	0,646	0,086
5	HRM4, QLT1, MGM1, TEC4, PAP2	235,225	136	0,108	1,73	0,911	0,647	0,080
6	HRM4, QLT1, MGM1, TEC4, PAP2, SUP4	196,955	119	0,157	1,655	0,925	0,647	0,076

Factor loadings for each item, as presented in Figure 37, are all above 0,6 which indicates that the proposed constructs are well reflected in the selected items (Abdul-Rashid et al., 2017; Danese et al., 2019; Vargas-Halabí et al., 2017), and therefore, confirming the validity the proposed measurement model. Table 43 shows that, as well as having high factor loadings, all of them are significant at a level of *p<0,005* (the probability of getting a sample value this far from zero if the population value is zero) after bias-corrected bootstrap standard errors.

Table 43. Lean manufacturing factor loads, average variance extracted and composite reliability

Construct	Item	Factor load[a]	p[b]	AVE	CR
HRM	HRM3	0,727	0,003	0,533	0,767
	HRM2	0,672	0,002		
	HRM1	0,787	0,002		
MGM	MGM4	0,757	0,002	0,538	0,733
	MGM3	0,677	0,002		
	MGM2	0,764	0,001		
PAP	PAP4	0,875	0,002	0,569	0,810
	PAP3	0,703	0,001		
	PAP1	0,668	0,002		
SUP	SUP4	0,648	0,001	0,567	0,825
	SUP3	0,785	0,001		
	SUP2	0,819	0,003		
	SUP1	0,748	0,001		
QLT	QLT4	0,782	0,002	0,642	0,816
	QLT3	0,813	0,002		
	QLT2	0,809	0,002		
TEC	TEC3	0,631	0,001	0,513	0,749
	TEC2	0,811	0,001		
	TEC1	0,694	0,002		

[a]Standardized
[b]Bias-corrected Bootstrap significance

Table 43 presents also the average variance extracted for each construct, and their composite reliability (CR). Convergent validity (i.e., the level of confluence between all items comprising a same construct) can be considered satisfactory for AVE values above 0,5 (Danese et al., 2019; Gualandris and Kalchschmidt, 2016; Sarmento and Costa, 2019), which was the case of all LM constructs. On the other hand, discriminant validity (i.e., the level to which the items for one construct are sufficiently different from the ones of the other constructs) can be assessed by examining the squares of the intra-construct correlations, in respect to the AVE for each construct (Chavez et al., 2013; Davcik, 2014; Sardana et al., 2020). In the case of the selected model, as Table 44 shows, the squared correlations are all bellow the AVE for each construct, with the exception of HRM-MGM and MGM-TEC. However, as Kim et al. (2016) suggest "*latent factors that compose one concept in the real world cannot be absolutely independent*". Since the MGM construct is considered one of the main pillars of lean implementation, it is expected that it presents a high correlation with all the other LM constructs. In this context, discriminant validity of the scale can be considered appropriate, also considering that the values from Table 44 are below the *0,85* threshold proposed by Kim et al. (2020).

Table 44. Discriminant validity of lean manufacturing constructs

	HRM	MGM	PAP	SUP	QLT	TEC
HRM	*0,533*					
MGM	0,810	*0,538*				
PAP	0,350	0,480	*0,569*			
SUP	0,340	0,320	0,430	*0,567*		
QLT	0,560	0,560	0,290	0,300	*0,642*	
TEC	0,590	0,810	0,590	0,450	0,620	*0,513*

Values bellow the diagonal represent the squares of intra-construct correlations
Values in the diagonal represent the AVE

Finally, although reliability was assessed in Section 3.5.2 by means of the Cronbach's α, in the context of CFA it can be more precisely evaluated by means of the composite reliability since it considers each item load and its measurement error (Shook et al., 2004). All factors presented evidence of good composite reliability with values exceeding 0,7 in all cases (Danese et al., 2019; Pérez-López et al., 2019).

As all measured items were draw from relevant literature and validated by an experts panel, it could be expected that factor loadings were high in all cases. However, to provide a valid measurement model some items were necessarily deleted as exposed in Table 42. Possible explanations for the low factor loadings and cross-loadings exhibited by the deleted items (HRM4, QLT1, MGM1, TEC4, PAP2) can be found when analyzing the descriptive results of the data sample presented in Section 3.4. Regarding HRM4, it can be argued that as most of the companies are small (Figure 27) the need multi-skilled personnel is most likely inherent to their manufacturing set-up (a low number of employees to cover multiple operations), rather than a conscious approach trough cross-training programs and other HRM practices. This can be a similar case with MGM1 and TEC4. Small Colombian companies are generally family owned and managed companies (Orozco and Aguirre, 2014), with strategies (business and manufacturing) defined according to the owner criterion rather than through strategic planning and development that involves all company areas and a close follow-up of external (macroeconomic and market) and internal indicators (such as OEE).

The low loading of standardized and continuous process flow (PAP2) could have two possible explanations. First, the large representation of SMEs in the sample, as continuous flow is most likely to be achieved in large processes-oriented companies, rather than in small job-shop manufacturing set-ups (Gahm et al., 2016). Second, the data could be affected by being collected during the COVID-19 pandemic, which forced almost all companies to make adjustments to their working conditions, thus traumatizing their process definitions and standardization. Finally, for the case of QLT1, it can be argued that since a large portion of the sample belongs to the automotive supply chain (Figure 30) customer expectations are clearly defined by technical specifications that are not easily changed by suppliers (and even by the assembly plants), therefore the efforts from companies are focused mainly on fulfilling those requirements in a cost-efficient and expedite way.

The sustainable performance measurement model was validated using the same CFA approach as in the lean manufacturing one. Since Table 41 confirms that the sustainable performance items do not exhibit multivariate normality, the Bollen-Stine bootstrap method was also employed in this case. Figure 38 presents the original measurement model for sustainable performance (the one comprising all items), while its corresponding fit indices can be found on Table 45.

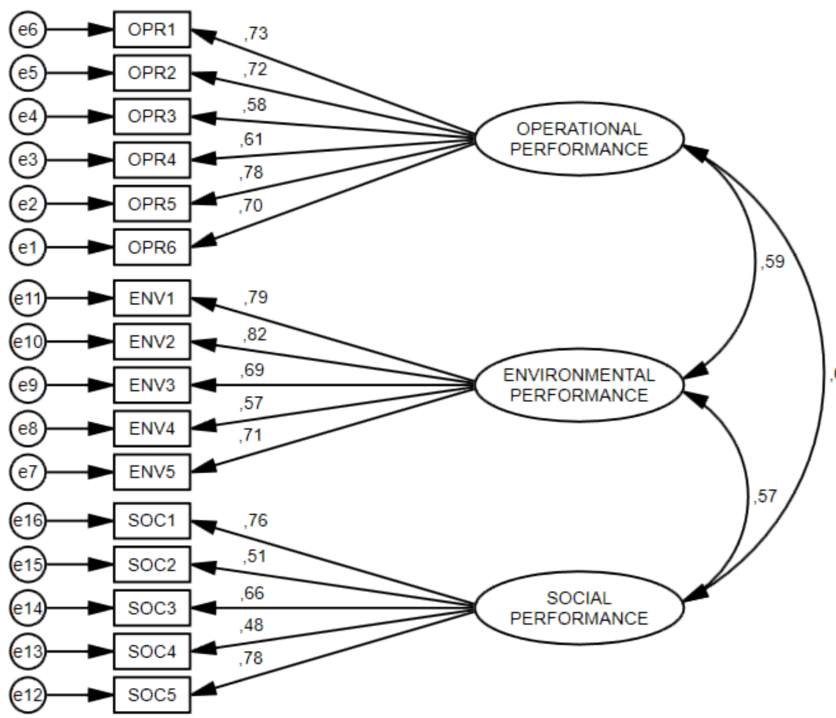

Figure 38. Original sustainable performance measurement model estimates

Although the original model presented a non-significant (therefore acceptable in terms of fit) BSp=0,308>*0,05*, and in general, relatively good fit indices, the factor loadings of some items were below the 0,6 threshold, as well as the AVE values for the constructs, indicating that the model did not have an acceptable level of convergent and discriminant validity. Therefore, as well as in the lean manufacturing measurement model case, the correlations matrix for all items was analyzed and items presenting low inter-construct and high intra-construct loads were individualized. Then, those items were iteratively eliminated from the model until the factor loads and AVE reached acceptable levels, and the general fit indices did not show a significant improvement.

Table 45. Sustainable performance measurement model fit indices

Model number	Deleted Items	χ^2	df	Bollen-Stine p	χ^2/df	CFI	PNFI	RMSEA
1	None	152,180	101	0,308	1,507	0,926	0,685	0,067
2	SOC4	120,146	87	0,462	1,381	0,949	0,698	0,058
3	ENV4	116,850	87	0,456	1,343	0,953	0,699	0,055
4	SOC4-ENV4	84,983	74	0,700	1,148	0,982	0,713	0,036
5	SOC4-ENV4-OPR3	75,911	62	0,572	1,224	0,975	0,701	0,045

Table 45 present the fit indices for all alternative measurement models considered, including the selected one (Model 5). Although Model 4 has slightly better fit indices than Model 5, the latter was preferred according to the model comparison criterion proposed by Arbuckle (2014). Model 4 has a χ^2 statistic of 84,983 and 74 degrees of freedom (df), while Model 5 χ^2 is 75,911 with 62 degrees of freedom. The χ^2 difference between both models is 9,072 with 12 df of difference. The significance level of a χ^2 value of 9,072 with 12 df is p=0,697>*0,05* which provides evidence to accept the null hypothesis of the model comparison (that Model 5 is better than Model 4).

The definitive sustainable performance measurement model (Model 5) is presented in Figure 39 with its corresponding factor loads for each item. Table 46 also presents the factor loads along with their bias-corrected bootstrap significance values, along with the AVE and CR for each construct. All items presented significant (*p<0,005*) factor loadings, with values exceeding 0,6 in all cases except for SOC2 (0,534) which is, however, acceptable according to many authors (Bortolotti, Boscari, et al., 2015; Katiyar et al., 2018; Machuca et al., 2011).

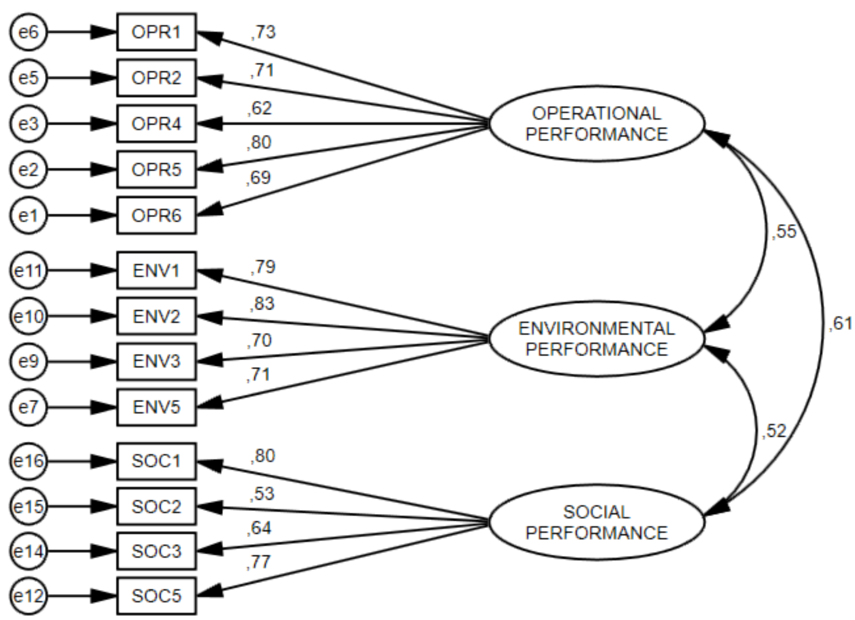

Figure 39. Final sustainable performance measurement model estimates

As it was the case with the LM measurement model, some items (SOC4-ENV4-OPR3) were deleted from the final sustainable performance measurement model in Figure 39. In the case of OPR3, it is possible that flexibility of the lot size is inherent to the job-shop manufacturing set-up of a vast majority of the SMEs comprising the data sample (Figure 27), rather than being as specific operational performance indicator. The large proportion of SMEs on the sample could also explain the exclusion of ENV4. All the retained environmental indicators are required to be monitored by all companies by Colombian laws and regulations. However, energy efficiency is not a law-requirement, therefore it is more likely to be closely monitored by large companies, as small ones are mainly focus on regulatory compliance. Finally, the exclusion of SOC4 is less straight forward under theoretical and practical grounds, as Colombian law mandate all companies to have a close reporting and follow-up of all job-related accidents. The sample size, which is noted as one of the limitations of the present research in Section 4.5, makes it difficult to replicate the models using control variables identified in literature such as company size (Shah and Ward, 2003), time of lean implementation (Čiarnienė and Vienažindienė, 2014), and market sector (Burawat, 2019), to identify if the low factor loading of said items persist in all control groups.

Table 46. Sustainable performance factor loads, average variance extracted and composite reliability

Construct	Item	Factor load[a]	p[b]	AVE	CR
OPR	OPR6	0,686	0,001	0,505	0,881
	OPR5	0,799	0,002		
	OPR4	0,624	0,001		
	OPR2	0,708	0,001		
	OPR1	0,726	0,001		
ENV	ENV5	0,706	0,001	0,573	0,862
	ENV3	0,701	0,001		
	ENV2	0,828	0,003		
	ENV1	0,785	0,003		
SOC	SOC5	0,771	0,002	0,481	0,830
	SOC3	0,637	0,001		
	SOC2	0,534	0,001		
	SOC1	0,799	0,001		

[a]Standardized
[b]Bias-corrected Bootstrap significance

Convergent validity was also validated by means of the AVE above 0,5 for each construct, except for Social Performance (SOC). SOC has an AVE of 0,481, which is close enough to the proposed threshold to ensure validity (Burawat (2019) proposes that an AVE above *0,4* is acceptable, as well as Kim et al. (2016)), and also considering that, first, the inter-construct item correlations are higher than the intra-construct item correlations (Chavez et al., 2013; Kull et al., 2014), and second, the resulting AVE value is greater than the square of the correlations between SOC and the other two constructs (Awan, 2019; Katiyar et al., 2018), as presented in Table 47. Finally, the composite reliability values for each construct in Table 46 further validate the internal consistency (reliability) of the proposed constructs, with all values exceeding the commonly employed threshold of *0,7*.

Table 47. Discriminant validity of sustainable performance constructs

	OPR	ENV	SOC
OPR	*0,505*		
ENV	0,303	*0,573*	
SOC	0,372	0,270	*0,481*

Table 48 presents a summary of the different fit indices employed to assess the overall fit for both measurement models (as presented in Table 42 and Table 45). Many authors suggest the use of the χ^2 statistic to test exact model fit. However, being an absolute fit test (Varela et al., 2019), χ^2 is prone to present a series of problems related to sample size, especially in the presence of high multivariate kurtosis (Curran et al., 2003), that could ultimately lead to the rejection of a model that has an acceptable fit because of minor misfits of no practical or theoretical significance (Corrêa Ferraz, 2020; Shook et al., 2004).

To cope with the troubles of relying only on χ^2 to assess model fit, many authors argue that multiple fit indices should be considered (Bagozzi and Yi, 2012; Curran et al., 2003; Fullerton et al., 2014; Shook et al., 2004). In that regard, Kim and Millsap (2014) state: "*In practice, researchers usually report the chi-square statistic and its significance, but seldom rely on it alone. In contrast to the exact fit test, global indices of approximate fit accept that a model does not fit perfectly and then quantify the degree of misfit. Strictly speaking, approximate fit indices do not support binary decisions of whether the model fits the data. Rather, approximate fit indices show the "relative" degree of model misfit*". This has led to adoption of other practical kinds of fit indicators, which can be measures of absolute fit, incremental fit, or parsimonious fit (Davcik, 2014; Losonci et al., 2017).

Table 48. Model fit indices and thresholds

Index	Description	Threshold	Type	References
χ^2	Chi square	*p>0,05*	Absolute	(Bagozzi and Yi, 2012; Davcik, 2014; Kim and Millsap, 2014; Schreiber et al., 2006)
χ^2/df	Chi square over degrees of freedom	*<3*	Absolute	(Bortolotti, Boscari, et al., 2015; Danese et al., 2019; Davcik, 2014; Losonci et al., 2017; Schreiber et al., 2006; Varela et al., 2019)
BSp	Bollen-Stine p	*p>0,05*	Comparative	(Arbuckle, 2014; Corrêa Ferraz, 2020; IBM, 2018; Kim and Millsap, 2014)
CFI	Comparative fit index	*>0,95 close fit* *>0,9 good fit* *>0,8 acceptable fit*	Comparative	(Bagozzi and Yi, 2012; Danese et al., 2019; Davcik, 2014; Losonci et al., 2017; Sarmento and Costa, 2019; Schreiber et al., 2006; Varela et al., 2019)
PNFI	Parsimony normed fit index	*>0,5*	Parsimonious	(Davcik, 2014; Losonci et al., 2017; Schreiber et al., 2006)
RMSEA	Root mean square error of approximation	*<0,05 close fit* *<0,08 fair fit* *<0,1 poor fit*	Absolute	(Danese et al., 2019; Davcik, 2014; Kim and Millsap, 2014; Losonci et al., 2017; Sarmento and Costa, 2019; Schreiber et al., 2006; Varela et al., 2019)

Absolute fit indices compare the obtained variables from the data sample against the implied structures of the proposed SEM or CFA models, hence the denomination of “absolute” as they do not compare the hypothesized model with other models (Davcik, 2014). Incremental (also called comparative) fit indices compare the fit of proposed models against a series of baseline models to evaluate to which degree they fit better (Curran et al., 2003). Finally, parsimonious fit indices account for model complexity, since most fit indices are significantly affected by it (Davcik, 2014).

To compensate for the possible biases and limitations of any single fit index, all models in this research will be evaluated using five different (commonly used in OM research) fit indices, with two of them being absolute (χ^2/df and RMSEA), two comparative (BSp and CFI), and one parsimony based (PNFI). Therefore, all indices on Table 48 will be presented not only for CFA models in this section, but also for SEM models in subsequent sections. It is important to notice that, while most authors agree on generally the same cut-off values or “rules of thumb” for the absolute indices, there is more discrepancy on literature regarding the comparative indices, especially CFI.

While some authors categorically reject models with CFI values below *0,9* (and even some suggest accepting only models above *0,95*), other authors point to many issues (especially in management and social sciences) that render unpractical said values, hence suggesting a CFI of *0,8* as the minimum acceptable value. In this regard, Sarmento and Costa (2019) state that “*comparative fit index (CFI) analyzes the model fit by examining the discrepancy between the data and the proposed model while adjusting for the issues of sample size intrinsic in the chi-squared test, and the normed fit index. It is considered very good if it is equal to or greater than 0,95, good between 0,9 and 0,95, suffering between 0,8 and 0,9 and bad if it is less than 0,8*”. Kim et al. (2016) report also good model fit for CFI values close to (even if below) *0,9*.

3.5.4. Sample size

As it was described on Section 3.3.3, the complete data set consists of 133 which represents 16% of the complete population census, and is in line with the response rates obtained by similar research in the same field (Abu et al., 2019; Sardana et al., 2020). Although according to Al-Abbadey (2020) current sample size guidelines for SEM remain arbitrary, in recent years researchers have come up with a series of “rules of thumb” to determine sample size, and some papers have been published evaluating the accuracy of said rules of thumb through simulations (Davcik, 2014; Kyriazos, 2018;

Wolf et al., 2013). In this way, in other to achieve a practical validation of the sample size obtained for this research, a comparison against common rules of thumb and general guidelines available in literature was performed.

One of the most cited guidelines refers to the samples for each regression path to be estimated or samples for each observed variable. Bagozzi and Yi (2012) found out that in cases where factor loadings are high (i.e. above 0,5), the observations to parameter ratio can easily be around 5:1, and they even found satisfactory models with 3:1 and 2:1 ratios, which, however, depend also of other variables, such as data distribution and model complexity. Kyriazos (2018) has also found that a 5:1 ratio can be used, as well as 5:1 for samples to items ratio. This is consequent with the findings of Davcik (2014) who agrees that a minimum of 5:1 ratio is acceptable, and reported that the average ratio in management studies present in literature is 6,4:1. In the case of the lean manufacturing construct, the obtained ratio is 7:1, and 10:1 for the sustainable performance construct.

In general, according to Wolf et al. (2013) for a model with similar characteristics to the sustainable performance measurement model in Figure 39, with 3 factors, 4 to 6 indicators per factor, factor loads of 0,72 (in average), correlations above 0,5, and no missing data, a minimum acceptable sample size of about 60 to 80 observations. For the case of the lean manufacturing measurement model in Figure 37 (6 factors, 3 to 4 indicators per factor, average factor loads of 0,75, correlations above 0,5) the minimum sample size goes up to about 100 observations, which, in either case, is below the achieved sample size in this research.

Another “rule of thumb” is cited by Gualandris and Kalchschmidt (2016) for SEM models. They state that the minimum acceptable sample size is obtained from multiplying by ten the greatest number of paths leading to a dependent variable. In the case of this research, the structural models proposed to test both hypothesis (presented in Figure 19 and Figure 20) have lean manufacturing as a second order latent variable, that has in turn six first order factors loading into it (the six constructs from the measurement model in Figure 37), therefore, six paths leading to it. Hence, according to Gualandris and Kalchschmidt (2016) in this case, a minimum of 60 observations are required.

It can be concluded that the sample size achieved for this research, meets the minimum requirements according to all the aforementioned criterions, wherever those are absolute (i.e., more than 100 observations (Bagozzi and Yi, 2012; Kyriazos, 2018)), a function of the estimated parameters and observed variables (19 items for lean manufacturing, and 13 for sustainable performance), the number of paths leading to a dependable variable, or the Monte Carlo simulations performed by Kyriazos (2018) and Wolf et al. (2013). The selected sample is also comparable to that of other previous research in LM using SEM, both in terms of the absolute number of respondents (s=133) and the sample size to construct ratio (s/c=14,7), such as those of Kamble et al. (2020) (s=115; s/c=8,2), Chavez et al. (2020) (s=104; s/c=26), Sardana et al. (2020) (s=58; s/c=14,5), and Dey et al. (2020) (s=119; s/c=10,8).

3.6. Structural models and hypotheses testing

Prior to evaluating the two proposed models that describe the effects of LM on sustainable performance, the effects of lean manufacturing on each one of the three TBL performance pillars, and the effect of LM on sustainable performance as a complete construct were evaluated. The main objective of this research (and the proposed hypotheses) concerns the nature of the effects of LM on sustainable performance, whether those are cumulative (hypothesis 1) or produce trade-offs (hypothesis 2). However, in order to properly develop said models, three different SEM models were proposed to evaluate the effect of LM on each performance dimension. More important, the results, as well as providing support to existing theories, will also be helpful to the interpretation of the results from the hypotheses models.

Therefore, Sections 3.6.1 to 3.6.3 explore the effects of LM on each single performance dimension alone. Section 3.6.4 test the effects of LM on sustainable performance as a complete construct, and finally, Sections 3.6.5 and 3.6.6 test the structural models for each one of the proposed hypotheses. Discussion and implications of the obtained results will be presented in Chapter 4.

3.6.1. Lean manufacturing effects on operational performance

The first proposed model evaluates the effects of lean manufacturing on operational performance. The resulting model along with its corresponding parameter estimates is presented in Figure 40. The corresponding model fit indices can be found on Table 49, which, compared to the suggested thresholds on Table 48, show that the Bollen-Stine bootstrap significance slightly below the *0,5* cutoff, and RMSEA is also slightly above the expected value. Despite this, the RMSEA value, although not below the optimal *0,08* threshold, is not above the *0,1* "reject" value, and all other indices meet the expected criterions.

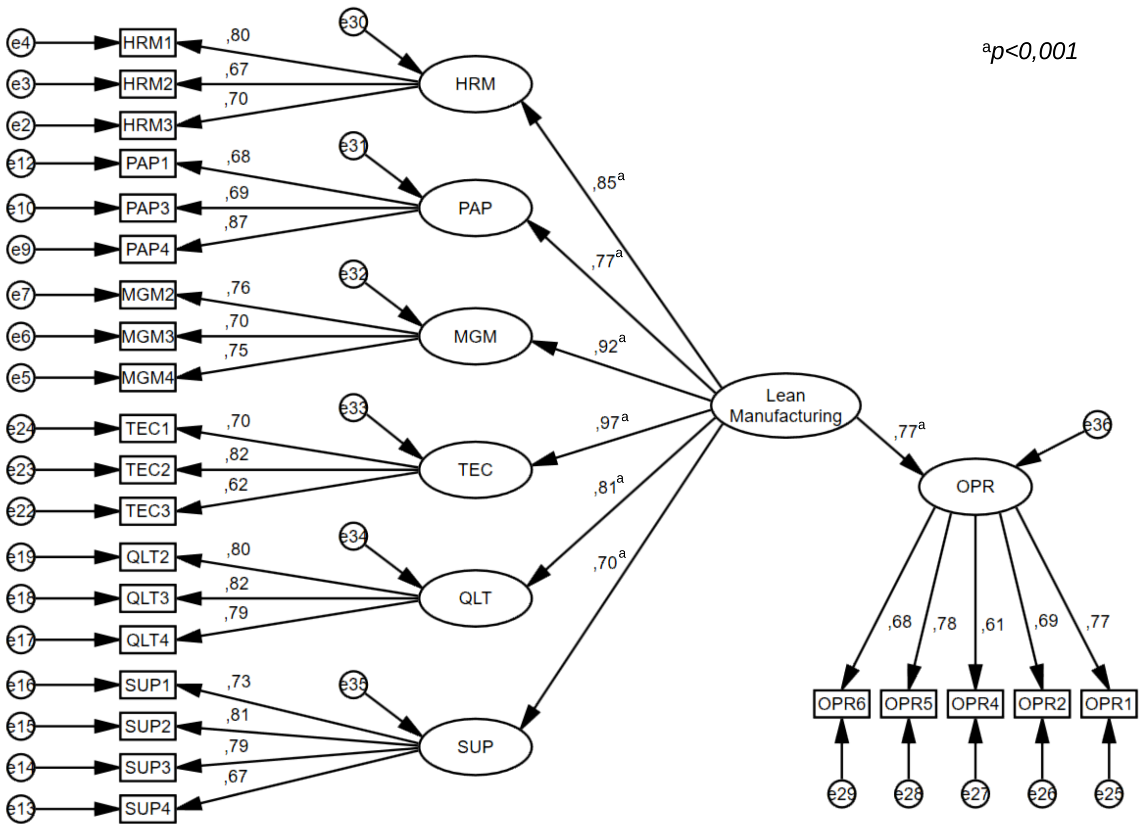

Figure 40. Lean manufacturing effects on operational performance

An analysis of the modification indices calculated by AMOS, did not provide any theoretically sound option to improve model fit. In this context, it can be said that the proposed model fit is not optimal, however, it can be considered acceptable. Figure 40 also reports the estimated standardized effect of lean manufacturing on operational performance (0,77; *p<0,001*), and the standardized regression weights (factor loadings) of the second order lean manufacturing construct on each one of the first order constructs of the measurement model, along with their corresponding significance, calculated using the bootstrap bias-corrected percentile method on AMOS, for a 90% confidence level. The factor loadings for each of the LM first order constructs on the observed variables, as well as those for the operational performance construct, correspond with those reported on the CFA (Section 3.5.3), along with their related significance levels in Table 43 and , therefore, the significance levels are not reported on Figure 40.

Table 49. Lean manufacturing effects on operational performance model fit indices

χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA
434,962	244	1,783	0,048	0,870	0,664	0,082

Given the obtained results, it can be concluded that lean manufacturing has a positive, statistically significant, effect on operational performance.

3.6.2. Lean manufacturing effects on environmental performance

The second proposed model is presented in Figure 41, evaluating the effect of LM on environmental performance. The model fit indices reported it Table 50 demonstrate that the proposed model has an acceptable fit, with only values slightly below the proposed threshold, but all other indices in line with Table 48.

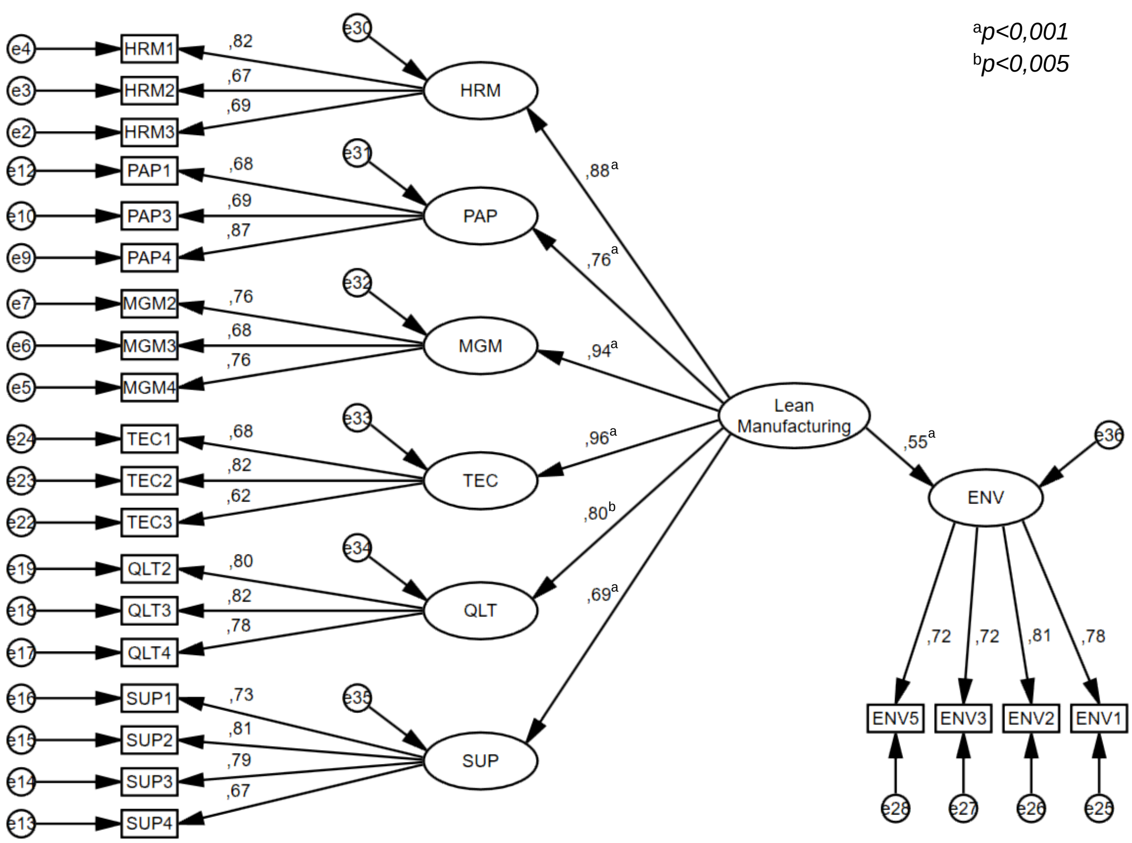

Figure 41. Lean manufacturing effects on environmental performance

With the assumption that the proposed model is correct, the standardized effects and bias-corrected bootstrap significance levels reported in Figure 41, allow to conclude that lean manufacturing has a statistically significant, positive effect on environmental performance (0,55; *p<0,001*).

Table 50. Lean manufacturing effects on environmental performance model fit indices

χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA
378,023	223	1,695	0,129	0,887	0,677	0,078

3.6.3. Lean manufacturing effects on social performance

The effect of LM on social performance is evaluated using the third proposed model, on Figure 42. In this case, LM also shows a positive effect on social performance, which, although having a lower significance level, can also be considered statistically significant. This conclusion is further supported by Table 51, showing that all fit indices fulfill the expected criterions.

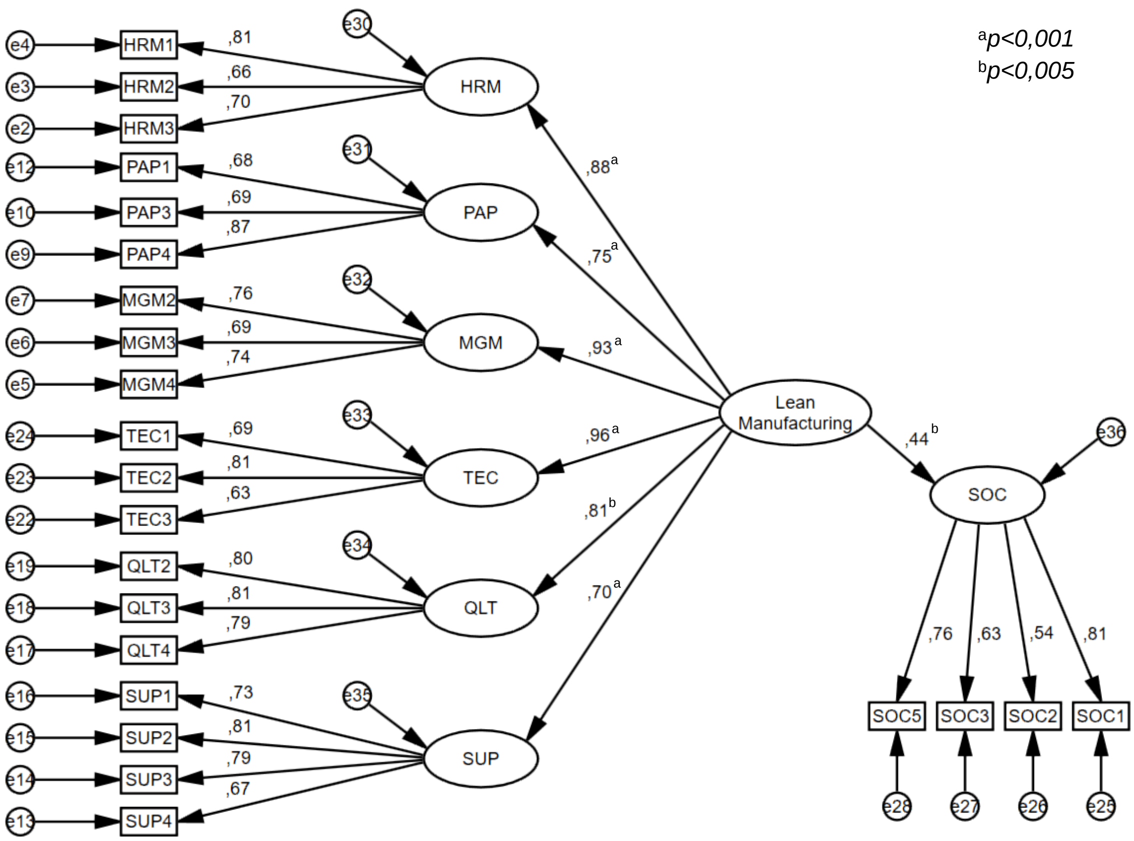

Figure 42. Lean manufacturing effects on social performance

Table 51. Lean manufacturing effects on social performance model fit indices

χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA
362,510	223	1,626	0,110	0,892	0,674	0,074

3.6.4. Lean manufacturing effects on sustainable performance

In the past three models, it was demonstrated that lean manufacturing has a positive and statistically significant effect on each one of the TBL performance pillars, when evaluated separately. The next proposed model tests the effect of LM on sustainable performance as a second order latent construct, composed by first order constructs representing each one of the TBL dimensions. Said model is presented on Figure 43. The model fit indices on Table 52 show an acceptable model fit, meeting the parameters of Table 48. Therefore, under the assumption that the model is correct, it can be concluded that LM has also a positive, strong, and statistically significant effect on sustainable performance (0,812; *p<0,001*).

Figure 43 also provides the standardized factor loads and bias-corrected bootstrap significance levels for each of the first order constructs (both for those loading on the LM second order construct, and those loading on the sustainable performance one). The results show strong (i.e., above *0,6*) factor loads, which support that the sustainable performance construct is indeed well reflected on each one of the three constructs representing the TBL pillars.

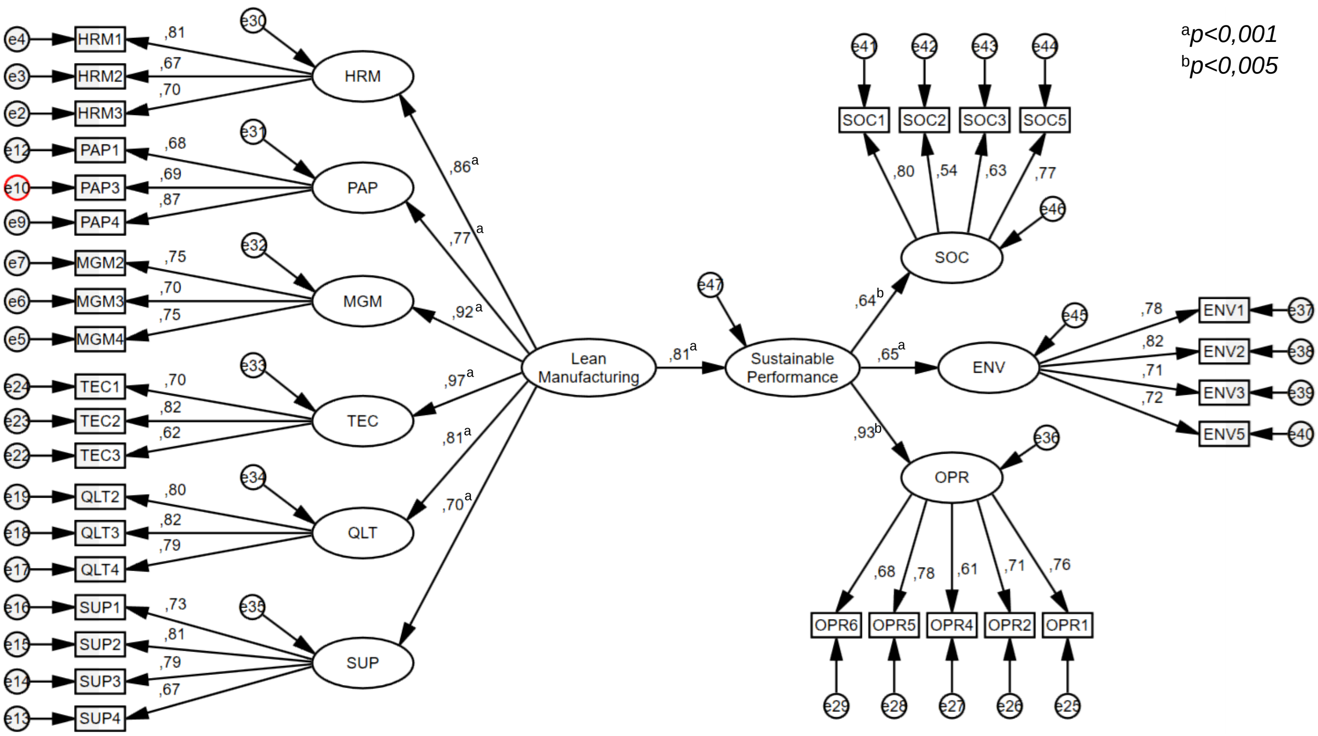

Figure 43. Lean manufacturing effects on sustainable performance

Table 52. Lean manufacturing effects on sustainable performance model fit indices

χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA
739.232	454	1,628	0,149	0,852	0,636	0,074

3.6.5. Hypothesis 1: cumulative approach

The first hypothesis, described in Section 2.3.1, propose a cumulative approach to sustainability in the presence of LM. In other words, it poses that LM has a positive effect on operational performance (already supported on Section 3.6.1), which in turn produces a positive effect (from operational performance) on environmental performance, and finally, environmental performance produces a positive effect on social performance. The structural equations model representing such hypothesis is presented in Figure 44.

The hypothetical model also assumes a direct effect of LM on environmental performance, and a direct effect on social performance. Although both positive effects (on social and environmental performance) were already evidenced on Sections 3.6.2 and 3.6.3, they were assessed separately on those models, without accounting for the interactions with the other pillars and the indirect effects that LM could produce through operational performance under the cumulative approach hypothesis.

The fit indices for the model are presented in Table 53, and show a good model fit. The significance levels of the estimated standardized effects show that the sequence of LM→OPR→ENV→SOC has positive and statistically significant effects, hence, confirming the validity of hypothesis 1. Instead, as Figure 44 shows, the estimated effects of LM on environmental performance and on social performance are not statistically significant, and therefore neglectable to the model.

Given that the LM→ENV and LM→SOC paths resulted not statistically significant, a specification search was performed to assess alternate models which might provide a better fit. AMOS provides the "Specification search" function to fit multiple models simultaneously, including (or excluding) some predefined regression paths and provides several indices to compare which model offers the better fit. The employed approach was that of a confirmatory specification search, as the measurement model remains invariable, and the structural model remains the same, only with five optional arrows (Arbuckle, 2014). All possible model subsets (a total of 32) were fitted.

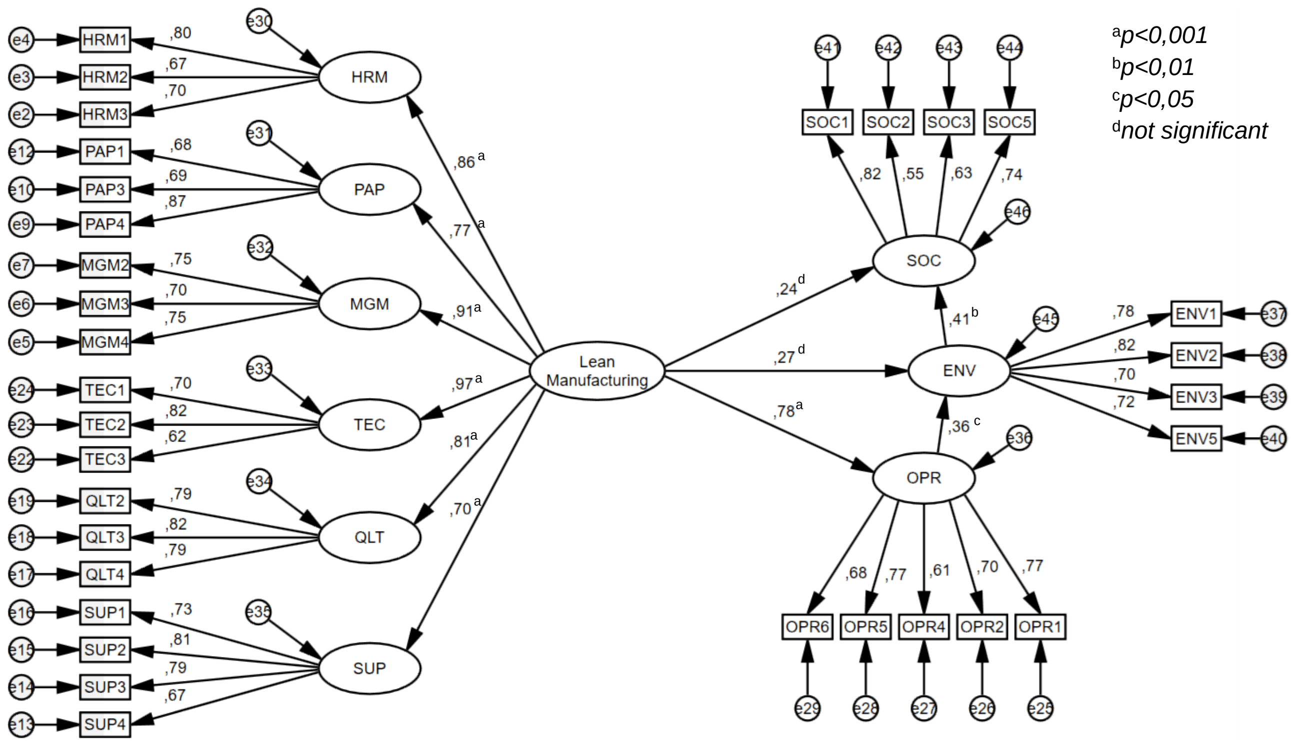

Figure 44. Lean manufacturing effect on sustainable performance: cumulative approach

Table 53. Cumulative approach model fit indices

χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA
742,262	453	1,639	0,141	0,850	0,633	0,075

Table 54 presents the results for the best models obtained from the specification search, with the first column showing which optional paths were erased from the base model in Figure 44. The Akaike information criterion (AIC_0), the Brown-Cudeck criterion (BCC_0), and the Bayes information criterion (BIC_0), are reported on the table and used as model comparison parameters. It is important to notice, that all three indices are presented in zero-based (normalized) form, which indicates that the best fitting model has a value of 0. All three statistics are intended only for model comparison, and not for single model evaluation (Iacobucci, 2010; Schreiber et al., 2006). Said measures compute a composite statistic that penalizes models for badness of fit and complexity, so simple, good fitting models receive low scores, and complex, poorly fitting models receive high scores (Arbuckle, 2014).

Table 54. Hypothesis 1 model specification search results

Excluded paths	χ^2	df	χ^2/df	CFI	RMSEA	AIC_0	BCC_0	BIC_0
None	742,262	453	1,639	0,850	0,075	0,000	0,560	2,932
LM→ENV	744,507	454	1,640	0,849	0,075	0,245	0,000	0,424
LM→ENV; LM→SOC	748,837	455	1,646	0,847	0,075	2,575	1,525	0,000
LM→SOC	746,151	454	1,644	0,848	0,075	1,889	1,644	2,067

The four best models according to the AIC_0, BCC_0, and BIC_0 criterions are displayed in Table 54. The original model in Figure 44 remains the best model according to the AIC, as well as the other reported fit indices (χ2/df, CFI and RMSEA). The best model according to the BCC criterion excludes the effect of LM on environmental performance, and, the best BIC criterion model, also excludes the effect of LM on social performance. According to the guidelines for interpretation of the comparison indices presented in Table 55, there is no significant evidence that the original model is in fact the best model according to the Kullback-Leibler discrepancy criterion (K-L best), therefore, the model in Figure 44 continues to be considered the correct one. In any case, since the effects of LM on environmental and social performance are not statistically significant in said model (as it was previously discussed), in practice, all four models on Table 54 are equivalent. This further supports hypothesis 1, meaning that LM has indeed a positive effect on operational performance, which in turns has an effect on environmental performance, and, finally, environmental performance also has a positive effect on social performance, producing the hypothesized “sand-cone” effect.

Table 55. Criterions for interpretation of model comparison indices. *Source: (Arbuckle, 2014)*

AIC_0 or BIC_0	Interpretation
0 - 2	There is no credible evidence that the model should be ruled out as being the actual K-L best model for the population of possible samples
2 - 4	There is weak evidence that the model is not the K-L best model
4 - 7	There is definitive evidence that the model is not the K-L best model
7 - 10	There is strong evidence that the model is not the K-L best model
> 10	There is very strong evidence that the model is not the K-L best model

Finally, it results interesting to analyze the standardized indirect effects of LM on environmental and social performance (through operational performance). On the Figure 44 model, LM has an indirect effect on environmental performance of 0,280 ($p<0,05$) and an indirect effect of 0,222 ($p<0,01$) on social performance. The total effect of LM on environmental performance is then 0,546 ($p<0,001$) and 0,466 ($p<0,005$) on social performance. This provides further, compelling evidence of a cumulative approach to sustainable performance in the presence of lean manufacturing, as about 50% of the total effect of LM on environmental and social performance is produced indirectly through operational performance. In other words, about half of the environmental and social performance improvements that can be achieved in the presence of lean manufacturing, come as a consequence of improvements on operational performance.

3.6.6. Hypothesis 2: trade-offs approach

The model proposed to test hypothesis 2 is a non-recursive model. Non-recursive models have bidirectional (reciprocal) paths from one variable to other (i.e. A has an effect on B, and B in turn has an effect on A), forming a continuous feedback loop (Finch and French, 2015; Nagase and Kano, 2017). Since hypothesis 2 poses that trade-offs occur among the different sustainability pillars, evidence of such trade-offs could be expected in the form of significant, positive effects on one direction of the non-recursive path, and significant, negative effects on the other one. As Figure 45 shows, there are reciprocal (i.e., non-recursive) paths between OPR-ENV, ENV-SOC, and SOC-OPR, which represent the hypothesized trade-offs.

Although the model in Figure 45 shows the expected (under the assumption that hypothesis 2 is correct) positive/negative relationships on each non-recursive loop, it is important to notice that said model, along with its corresponding results and estimates is not valid. The reason for this is that the model is considered unstable, which is an important condition that non-recursive models must met. In a stable model, the reciprocal regressions converge to a set of well-defined relationships, while in an unstable model, said regressions form an infinite sequence of linear dependencies for which, accurate regression weights cannot be estimated (Gempp and González-Carrasco, 2021).

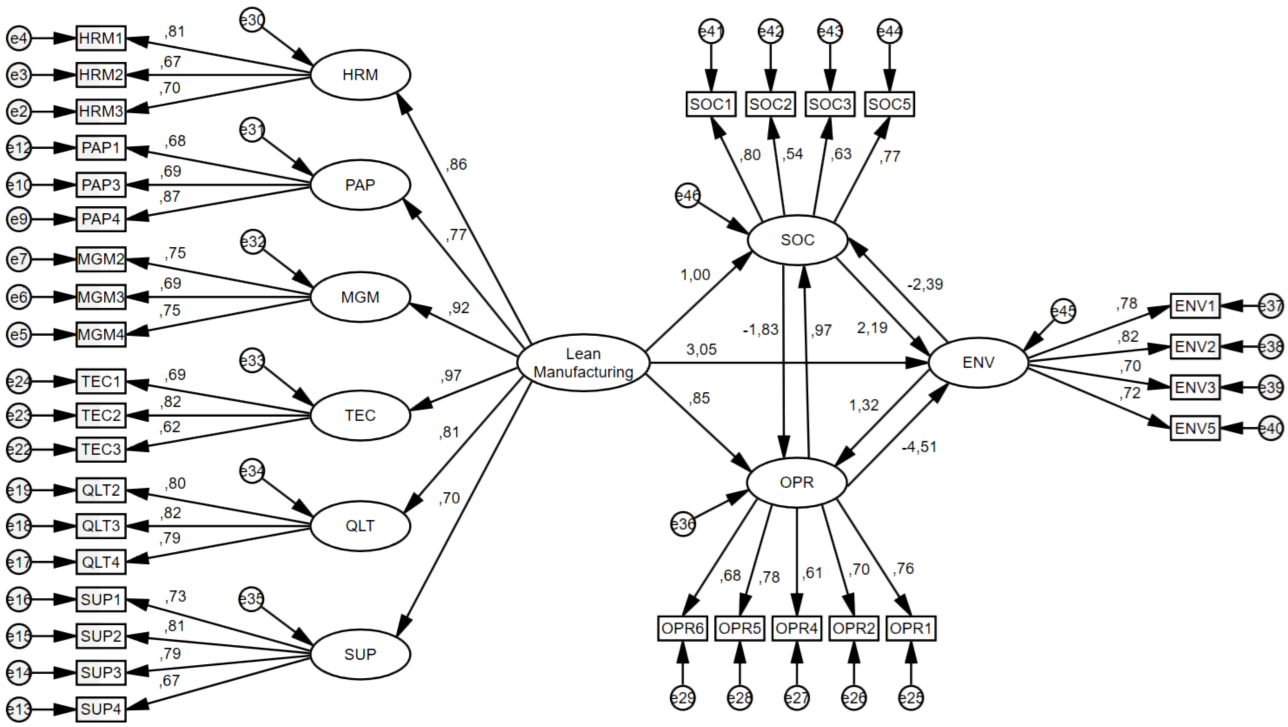

Figure 45. Lean manufacturing effect on sustainable performance: trade-offs approach

To assess model stability, AMOS computes a "stability index", that must fall between -1 and 1 to consider the model stable (Arbuckle, 2014; Gempp and González-Carrasco, 2021). In this regard, Arbuckle (2014) states that "*an unstable system (with a stability index equal to or greater than 1) is impossible, in the same sense that, for example, a negative variance is impossible. If you do obtain a stability index of 1 (or greater than 1), this implies that your model is wrong or that your sample size is too small to provide accurate estimates of the regression weights. If there are several loops in a path diagram, Amos computes a stability index for each one. If any one of the stability indices equals or exceeds 1, the linear system is unstable*". For the model presented in Figure 45 the Stability index was 14,341, evidencing that the model is unstable, and therefore, not valid. For this reason, no fit indices are reported for this model.

Although having an unstable model does not allow to prove hypothesis 2, a series of alternative models were proposed and tested in order to evidence (or reject) other possible trade-offs among the variables. The first approach was to conduct an exploratory specification search, leaving all structural paths as optional. This means, AMOS would try to find the best model excluding any (or all) of the following paths: LM→OPR, LM→ENV, LM→SOC, OPR→ENV, ENV→OPR, OPR→SOC, SOC→OPR, ENV→SOC, and SOC→ENV. Interestingly, the results of the specification search pointed that the best fitting model on the subset is the one of hypothesis 1 (Figure 44).

A second approach consisted of evaluating the different possible trade-offs sets independently. Having a lesser number of non-recursive loops can improve the stability of the models. Therefore, three alternative models (presented in Figure 46, Figure 47, and Figure 48) were tested. Their correspondent fit indices in Table 56 show that all three models have acceptable fit. Also, the last column shows the stability index (SI) for each model, which, in all cases, falls between the expected -1 to 1 range, thus, confirming that all models are stable. Although Table 56 shows the fit indices for all models in a single table, it was done for space-saving purposes, and not for comparative purposes. Hence, all three models will be evaluated separately, and considered valid independently.

The first alternative trade-offs model, in Figure 46, shows a positive/negative reciprocal effect between operational and environmental performance. However, both regression weights are not statistically significant, and therefore, neglectable. In this context, there is no evidence of trade-offs between operational and environmental performance in the presence of lean manufacturing.

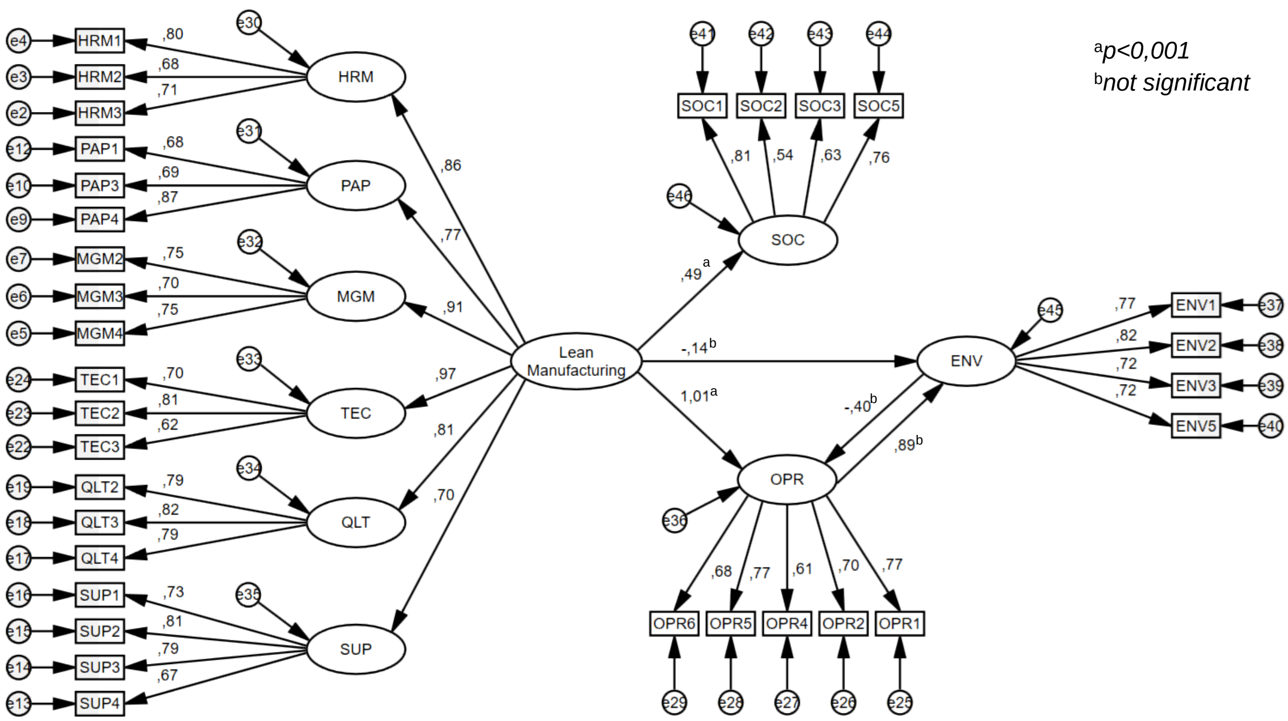

Figure 46. Alternative trade-offs model 1: OPR-ENV

A particularity of non-recursive models that can be appreciated in Figure 46, as well as in Figure 47, is that standardized regression weights can exceed 1. This can be produced by the continuous feed-back loop that characterize non-recursive models, and it does not mean that it is incorrect (Lai et al., 2017). Standardized regression weights often fall in the range between -1 and 1, leading to the believe that they cannot be valid above 1. However, as Jöreskog (1999) pointed out, "*the misunderstanding probably stems from classical exploratory factor analysis where factor loadings are correlations if a correlation matrix is analyzed and the factors are standardized and uncorrelated (orthogonal). However, if the factors are correlated (oblique), the factor loadings are regression coefficients and not correlations and as such they can be larger than one in magnitude. This can indeed happen also for any factor loading or structural coefficient in any LISREL model. Just remember that a standardized coefficient of 1.04, 1.40, or even 2.80 does not necessarily imply that something is wrong*".

The second model, presented in Figure 47, is a good fitting and stable model (according to the data on Table 56), therefore, it can be considered valid. Interestingly, the model shows a statistically significant and positive effect of social performance on operational performance, while it also presents a statistically significant and negative effect of operational performance on social performance. This points to a trade-off between those two dimensions of sustainability in the presence of lean manufacturing.

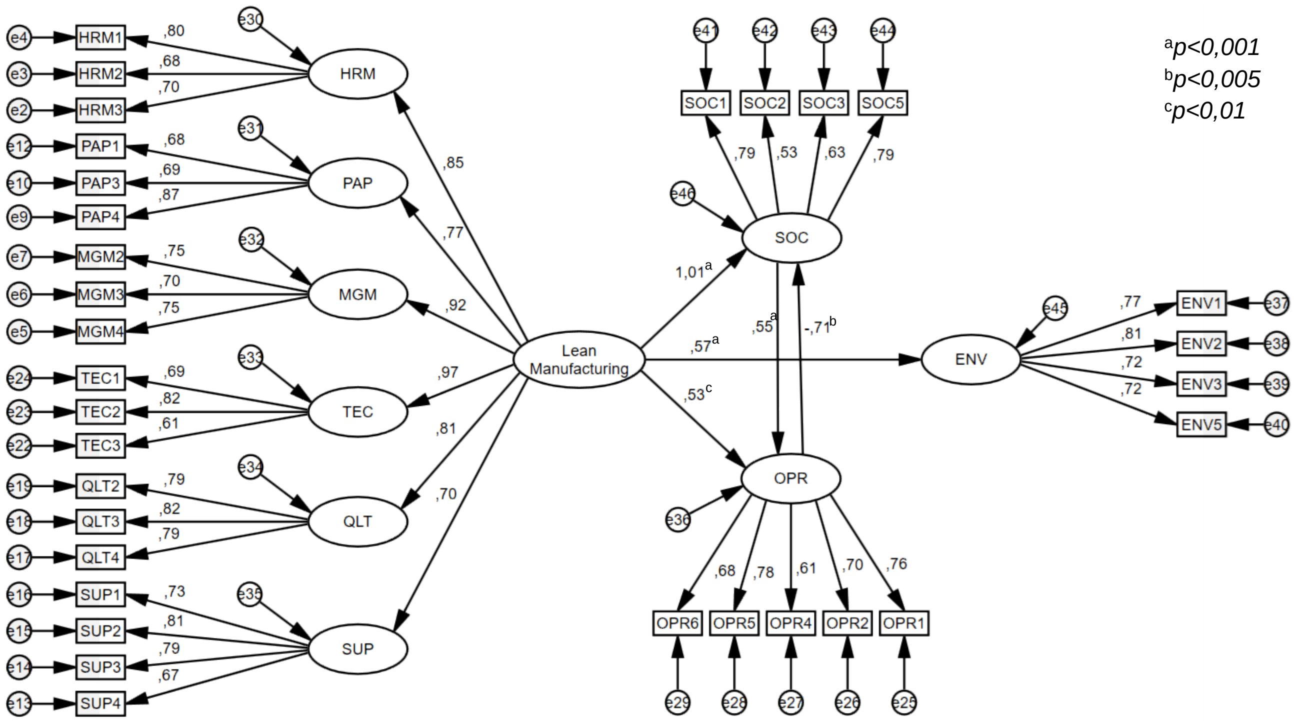

Figure 47. Alternative trade-offs model 2: SOC-OPR

The effects of LM on SOC, ENV and OPR, in Figure 47 are all positive and statistically significant. Therefore, the results can be interpreted as follows: LM has a positive effect in operational, environmental, and social performance, however, while the positive effect on social performance translates into a positive effect on operational performance, the positive effect (from LM) on operational performance creates a negative effect in social performance. In other words, improvements generated in operational performance from the implementation of LM create a detriment in social performance. The same evidence of trade-offs can be found analyzing the direct and indirect effects. On the model presented in Figure 47, LM has a direct effect on SOC of 1,01 (*p<0,001*). However, it has an indirect effect (through OPR) of -0,552 (*p<0,005*).

For the third alternative model (in Figure 48), the behavior is similar to that of the second one. The model exhibits evidence of trade-offs between social and environmental performance. SOC has a positive and statistically significant effect on ENV (0,852; *p<0,005*), while ENV has a negative and statistically significant effect on SOC (-0,867; *p<0,005*). Also, while the direct effect of LM on environmental performance is not statistically significant, the indirect effect of LM on social performance (through ENV) is indeed statistically significant and negative (-0,490; *p<0,005*). On the other hand, the indirect effect of LM on ENV (through SOC) is 0,407 (*p<0,001*).

The results of the second and third alternative models provide partial support to the trade-offs hypothesis, with evidence pointing to trade-offs occurring with the social performance dimension. In other words, the data shows that lean manufacturing has negative indirect effects on social performance, both through operational performance and through environmental performance.

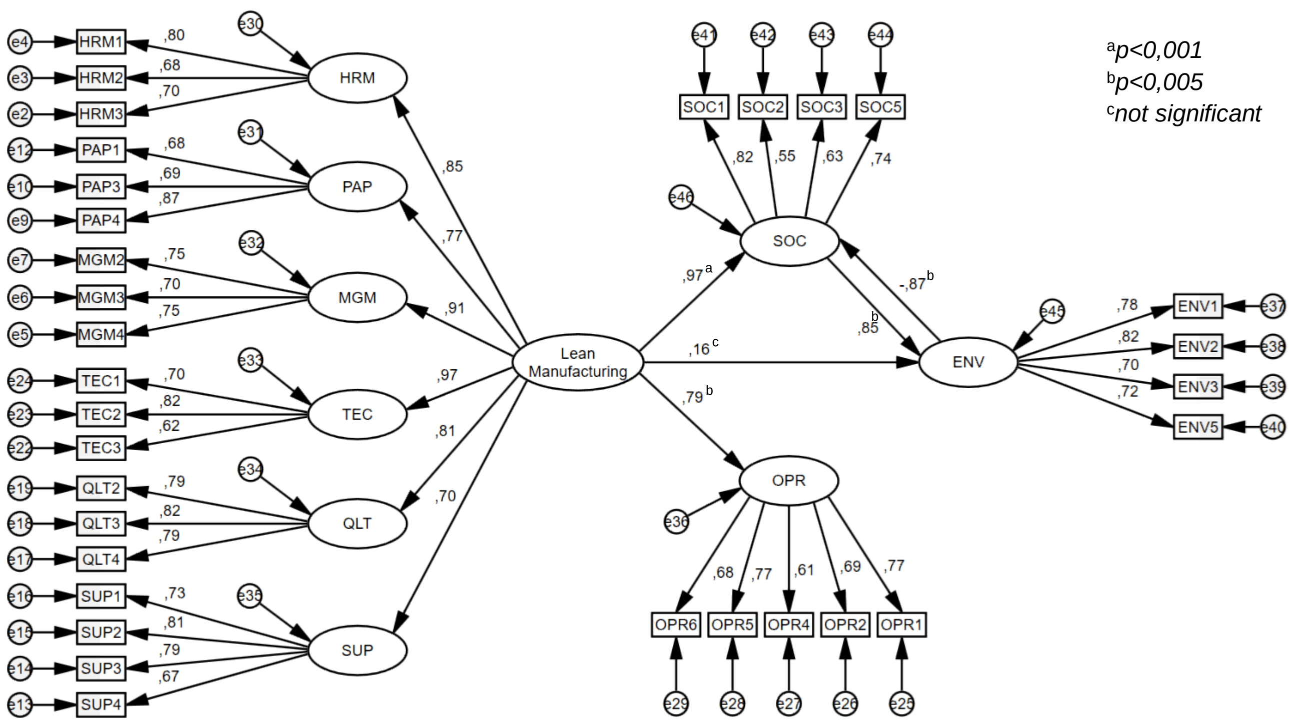

Figure 48. Alternative trade-offs model 3: ENV-SOC

Table 56. Alternative trade-offs models fit indices

Model	χ^2	df	χ^2/df	BSp	CFI	PNFI	RMSEA	SI
Figure 46	752,308	454	1,657	0,128	0,845	0,631	0,076	0,356
Figure 47	743,707	454	1,638	0,145	0,849	0,634	0,074	0,389
Figure 48	746,252	454	1,644	0,140	0,848	0,633	0,075	0,738

3.7. Partial conclusions

From the present chapter, it can be concluded that the data collection instrument developed from the state-of-the-art literature in both lean manufacturing and sustainability fields, is appropriate and valid for the purposes of this research. It constitutes an important contribution for research purposes, as it provides a battery of variable useful for assessment of both lean manufacturing implementation level, and sustainable performance on all three TBL pillars. It also represents a practical contribution as it gives companies and managers an assessment framework to evaluate their progress in bath measured variables, and it can even result useful to compare themselves to other companies from similar sectors and contexts.

Important conclusions can be drawn also from the final sample of companies participating in the research. It can be said that Colombian metalworking industry is mainly composed by small companies, however, medium, and large ones are present in representative percentages. Regarding the lean manufacturing implementation level, the majority of companies have a medium to high level of implementation on all constructs, with planning and processes and human resource management constructs being the most developed constructs. In contrast, management commitment and technology, while still having most companies in a medium or above level, were the more relegated constructs. This points to companies favoring the implementation of the so-called lean "soft" practices, which require lower investments in technologies and resources compared to the "hard" practices.

Regarding the performance of companies in all TBL dimensions, only a minor part of the companies (less than 5%) perceived detriments in any dimension of performance after implementing lean manufacturing. Interestingly, the more solid improvements were perceived in the social dimension, which could be an indirect consequence of increasingly stricter labor regulations in the country during the last decades as a result of external pressures, such as free trade agreements signed with north America and European countries. Nevertheless, more than half of the companies also perceived improvements in operational performance (as expected during a successful lean implementation), while a little less than half of them perceived some improvements on environmental performance.

The structural model results allow to conclude that lean manufacturing has positive results on each one of the triple bottom-line pillars when the relationships of lean with each pillar are considered independently. The results also support the proposed "sand-cone" approach of hypothesis 1, where lean manufacturing has positive effects on operational performance, that in turn generate improvements in environmental performance, and ultimately lead also to improved social performance. This model also shows that there are strong indirect effects of lean on environmental and social performance (through operational performance), which are consistent with suggestions in literature of "green spillovers", or positive side effects of the implementation of lean on environmental outcomes. Instead, to the author knowledge, it is the first time that "social spillovers" of lean are evidenced based on empirical data.

In regard to the second hypothesis, the results are less conclusive, with no evidence suggesting trade-offs among all sustainability pillars in the presence of lean. However, models testing independently possible trade-offs between pairs of the TBL pillars, provided evidence of detrimental effects on social performance as a consequence of improvements on operational performance and environmental performance, but only when each two performance dimensions were analyzed independently.

The results obtained from all the tested models clearly provide the required information to answer the proposed research questions for this research, as well as closing the identified knowledge gap by providing empirical evidence that lean manufacturing can effectively have a positive effect on sustainable performance, especially if a cumulative sequence of performance improvement on each TBL pillar is employed instead of a concurrent approach.

CHAPTER 4. DISCUSSION AND CONCLUSIONS

4.1. Results discussion

4.1.1. Lean manufacturing effects on performance dimensions

Sections 3.6.1 through 3.6.3 showed that for the data sample, lean manufacturing has positive effects on operational, environmental, and social performance, when evaluated separately. Although it was not ne main objective of this research to prove the effects of LM on each TBL pillar individually, the results are valuable both to provide further support to existing theoretical bases, as well as to provide grounds that enhance the understanding and interpretation of the tested hypothesis.

Several interesting points can be extracted from these results. First, the magnitude of the effects varies among the TBL dimensions, with the LM effect on operational performance being the largest (0,77; $p<0,001$), while the effect on environmental performance is lower (0,55; $p<0,001$), and the effect on social performance the lowest (0,44; $p<0,005$). This result concurs with current theoretical positions, and results of several previous research that have demonstrated the benefits that lean manufacturing pose to operational performance.

The main tools and practices comprising LM were originally developed to improve variables associated to operational performance such as cost, lead time, flexibility, quality, and inventories, whether those practices were applied as “stand-alone” tools or as an integrated philosophy (Liker, 2004; Shah and Ward, 2003). It was hence expected that the effect of LM on the sample companies were indeed positive and strong, in line with plenty of previous empirical evidence, that, although not previously proven in the context of Colombian industry (to the authors knowledge), has support in several other developing countries like Brazil, India, Thailand, Jordan and Turkey (Belekoukias et al., 2014; Khanchanapong et al., 2014; Negrão et al., 2017; Shrafat and Ismail, 2019).

Previous studies such as that of González Gaitán et al. (2018) evidenced to a certain level (on a sample composed by textile industries from the Antioquia region in Colombia) that there is a sufficient level of commitment of managers to LM implementation in Colombian companies, and that they are also aware of the potential benefits on some operational measures (like quality and cost). However, conclusive empirical evidence of the manifestation of said benefits is not presented. León et al. (2017) employed a multi-case study, on five Colombian companies from different manufacturing sectors, to identify critical success factors (CSF) for LM implementation. On their conclusions they point to management commitment and long-term orientation (of lean programs) as some of the CSFs present, and suggest that the studied companies have achieved some performance improvements, without specifying on which dimensions or variables.

The obtained results on this research contribute empirical evidence to support previous claims of González Gaitán et al. (2018) and León et al. (2017), and provide a further understanding of how LM implementation positively impacts operational performance on Colombian industries. From Figure 34 it can be seen that most of the sample companies had medium, high, or superior management commitment levels towards lean manufacturing, which can be then considered as one of the contributing aspects of the positive results obtained in Figure 40. Figure 31 also shows that, in average, sample companies have been implementing LM for four years. Although it does not necessarily point to a long term commitment of all the companies, at least most of them have passed the "loss of interest" and "back to the old ways" time of about two years after initial lean implementation (León et al., 2017; Poksinska and Swartling, 2018; Sadiq et al., 2021). Therefore, previous studies suggest that most of the sample companies should be at least starting to perceive operational, and the results of Figure 40 provide evidence of such claim. Finally, the results corroborate which operational performance measures are positively affected by LM, evidenced by the strong and significant factor loadings on Figure 40. Said performance indicators are cost, quality, production lead-time, cycle time (manufacturing cadence), and work in process inventory. Regarding lot size flexibility, since that indicator had to be removed from the operational performance construct during the CFA, it is not possible to provide evidence concerning how LM impacts it.

In regard to environmental performance, Leguízamo-Díaz and Moreno-Mantilla (2014) had previously provided evidences that lean manufacturing (considering quality, supply, and process related practices) has a mediating effect between quality and delivery, that translates into a positive effect on green supply chain management (GSCM) practices, represented by product surveillance, shared vision, eco-efficiency, monitoring, and waste handling (with many of the items comprising said practices being environmental performance variables in the present research). Their sample was composed by 129 Colombian companies from Bogota, with 64 of them being manufacturing companies. Incidentally, the standardized effect of LM on GSCM in their research was of 0,56 ($p<0,01$), which results almost identical to the effect of LM on environmental performance presented on Figure 41 (0,55; $p<0,001$). Considering that the sample was different and the variables employed to measure each construct were not exactly the same, the closeness of the results can be considered a coincidence. However, the evidence from both studies confirms that Colombian companies implementing lean manufacturing practices perceive environmental benefits in doing so.

Although no more studies linking LM to environmental performance in the context of Colombian industries were found in the reviewed literature, there are several other studies around the world that present similar evidence of positive LM-environmental performance relationship. Many of them can be found on Garza-Reyes (2015) literature review, who concluded that while many studies suggest a beneficial effect of LM on different performance dimensions (that include environmental), this is particularly true when organizations implement jointly lean and green practices. Also, he concludes that, due to other studies not presenting consistent conclusions, research on this regard is still limited and inconclusive. This comes in line with the review presented in Section 1.6.2, which highlight some evidences of LM having no impact, or negative impact, on environmental performance, such as those pointed by Bandehnezhad et al., (2012), Bergenwall et al. (2012), and Martínez León and Calvo-Amodio (2017), among others.

The results of Figure 41 adds to existing evidence of positive effects of LM on environmental performance, however, it is by no means enough to draw definitive, generalizable conclusions on the matter (and it is not the objective of this research). However, there is an interesting and novel contribution that can be extracted from the results presented in Sections 3.6.2 and 3.6.5, and it is related to the nature of how LM impacts environmental performance. It has been suggested by authors such as Piercy and Rich (2015) and Resta et al. (2016) that environmental benefits derived from lean manufacturing implementation are side-effects, rather than direct effects. This is called "*the law of the expected unexpected side benefits*" by Corbett and Klassen (2006), and, although frequently cited in literature, empirical evidence confirming this suggestion has been scarce.

In light of the obtained results, it can be concluded that, while LM has a significant, positive effect on environmental performance when evaluated separately (without accounting for all performance dimensions), that effect becomes not statistically significant when assessed in the presence of all TBL performance dimensions, as shown in Figure 44 (0,27; $p>0,05$). Instead, when considering all TBL dimensions, there is a significant positive indirect effect of LM on environmental performance through operational performance (0,28; $p<0,05$). This provides evidence of said "green spillovers" or green side-effects of LM.

A possible explanation for this is that LM practices have been designed to impact operational measures, however, the maturity and organizational commitment level required to achieve a successful implementation of LM, eases the adoption of green practices that have themselves the aim to impact environmental measures. This notion can be partially supported by the results of the case study presented in Section 3.2.2. While interviewing the tactical-level group, the plant supervisors and other personnel in charge of leading the implementation of some lean tools, recalled that as the implemented tools began to produce tangible results, the plant management committed more resources to continue with the implementation of other practices, that where not necessarily related to the "core" of lean. One example was the implementation of a 3Rs program (recycle, reuse, reduce) that came as a spin-off of the implementation of 5S, when the employees started proposing ideas of what to do with the surplus elements that arose after implementing *Seiri* (the first of the 5S).

Finally, the results concerning the impact of LM on social performance constitute an important contribution of this research. As it has been pointed out by many authors, the LM – social performance relationship has been the less studied (Distelhorst et al., 2017; Longoni, 2014; Sahoo, 2020; Souza et al., 2018), and research results still present several contradictions. On one hand, recent studies like those of Chavez et al. (2020), Kamble et al. (2020), and Sajan et al. (2017) have found empirical evidence of a positive LM-SOC relationship, however, their results were provided in a context that accounted for all TBL dimensions. This raises the question of: does the positive effects of LM on SOC are directly associated to the implementation of lean, or instead, come as a by-product of operational and environmental improvements?. That is not a new question in the matter, with Silva et al. (2013) raising concerns that in their study of a Portuguese manufacturing company, "*the main effects of Lean Manufacturing on environmental and social sustainability turned out to be directly related to the reduction of cost through reduction of unnecessary transportation, manufacturing time and materials consumption*".

On the other hand, previous research have also provided evidence of neglectable, or even negative, effects of LM on social outcomes. Distelhorst et al. (2017) expected an improvement on health and safety standards (derived from employee involvement and standardization), that failed to materialize in their results, similar to the case of Varela et al. (2019). Moreover, studies such as those of Bergenwall et al. (2012) and Longoni et al. (2013) found that some lean practices can be detrimental of some social performance indicators, such as, employee motivation, job security, and even safety. De Freitas et al. (2017) suggest that a possible explanation for these negative effects comes from the pressure generated on employees to improve operational and financial outcomes.

The results of Figure 42 provide new insights into the ongoing debate in literature. To the question: does LM has a positive effect on social performance?, the answer, in light of the results should be, yes. Though, said effect is relatively small (0,44; $p<0,005$) in respect to the effect of LM on operational and environmental performance, and it is reflected on improved wages and economic compensation, new direct and formal workplaces creation, employee turnover rate, and employee satisfaction and motivation. Regarding the accident rate, the items had to be removed from the construct due to low factor loadings, so it was not possible to assess its behavior in the presence of lean, which adds to the uncertainty around the matter already raised by Distelhorst et al. (2017) and Longoni et al. (2013).

On the other hand, when the question becomes: is the positive effect of LM on SOC a direct effect, or a side-effect of lean implementation?, the answer, in light of the results in Figure 44, points to lean not having a significant direct effect on SOC, and instead, most of the positive impacts of lean on social outcomes being an indirect effect of the improvements on operational and environmental performance (0,22; $p<0,01$). As it was remarked in Section 3.6.5, the indirect effects of LM on SOC account for half of the total effects. As it was the case of the indirect effects of LM on ENV, it seems that lean practices are not enough to make a significant impact on SOC, but settle the grounds for the implementation of further practices that have a social aim, and the improvements in OPR measures pervade resources to invest in said kind of practices.

Interestingly, when de Freitas et al. (2017) and Varela et al. (2019) tested the effects of LM on all TBL pillars of sustainability, they results did not find significant positive effects of LM on SOC, as they only searched for direct effects. In the light of the results from the present research, de Freitas and Varela's findings were the most likely scenario as they did not considered interactions (indirect effects) with the other pillars of TBL. This was similar to the case of Distelhorst et al. (2017) and Longoni et al. (2013) who only considered the social pillar of TBL, leading to adverse findings. In those cases, the other authors argued of the high and long-term investments needed to improve some social indicators, the possible detriments to worker motivation from standardized tasks and cross-training, and the lack of integration of lean with other sustainability paradigms as the possible causes to their findings. However, current findings support that the likely cause (with empirical evidence, at least on the context of the present research) was not considering the contributions that LM can provide through the improvements on operational and environmental outcomes.

4.1.2. Lean manufacturing effect on sustainable performance

The effects of lean manufacturing on sustainable performance has become a topic of growing interest in the last ten years (Burawat, 2019; Henao et al., 2019), with a growing number of publications addressing the matter, especially in the last five years (Farias et al., 2019). A significant part of studies in recent years consists of empirical works, with a large amount of them being conducted in the context of developing countries, such as India (Kamble et al., 2020; Katiyar et al., 2018; Sajan et al., 2017; Venugopal and Saleeshya, 2019), Thailand (Burawat, 2019), Chile (Chavez et al., 2020), Malaysia (Abdul-Rashid et al., 2017), and Egypt (Abobakr and Abdel-Kader, 2017). Interestingly, few recent empirical studies have explored the relationships between lean and sustainability in developed economies, except (to the author knowledge) for that of Varela et al. (2019) which was conducted in Portugal and Spain.

Bearing in mind that the present research was also conducted in the context of an emerging economy, the discussion of its results in contrast to previous works in literature allow to draw an interesting parallel on said context. It remains, however, a latent knowledge gap if current empirical trends can be generalized to developed countries. The results in Figure 43 suggest that for the sample of Colombian companies, lean manufacturing has a strong positive effect on sustainable performance (0,812; *p<0,001*). In this case, the standardized effect of LM on sustainable performance (measured as a second order latent construct), is even larger than the standardized effects of LM on each TBL pillar discussed on the previous section. This was by no means an expected result, as the effects of LM on sustainability are still a topic of ongoing debate on literature, with Resta et al. (2016) claiming that "*more empirical research is needed to fully address the benefits of LM for sustainability, which while previously suggested, have never been fully explored across a range of industrial sectors and case studies*".

The positive effects of LM on sustainable performance evidenced in the model proposed in Figure 43, come straightforward from the results on Figure 40, Figure 41, and Figure 42, where LM was found to have positive effects on each TBL pillar individually, therefore, suggesting a positive effect also on the sustainability construct. This however contrast with some results of previous research. In fact, previous studies tend to vary in their conclusions depending if the effects of LM are tested on a single sustainable performance construct (whether being a second order construct as the case of this research, or a first order construct comprised by items from all TBL pillars), as in Figure 43, or on each one of the TBL pillars simultaneously, as in Figure 44. It seems that LM tend to favor sustainable performance improvement in the cases when sustainability is considered as a single construct, such as is the case of Burawat (2019), Kamble et al. (2020), and Katiyar et al. (2018).

The positive LM – sustainable performance effect, in consequent with Burawat (2019), who found also evidences of such relationship, mediated by the effect of sustainable leadership. Interestingly, his results show that said effect is higher in automotive companies than in other manufacturing companies. Although the number of companies on the available sample for this research does not allow to test the structural models while controlling for market sector, the results of Figure 30 shows that the automotive industry is the most largely represented in the sample. As it was already discussed in Section 3.4, companies related to the automotive industry are more prone to the implementation of lean practices, which are even a customer requirement in some cases. It is also likely that automotive industry companies have been implementing lean practices for a longer time (Burawat, 2019), therefore, they could have achieved more significant performance improvements from said practices, and have more "mature" manufacturing systems that allow to extend those improvements into environmental and social benefits.

The above reasoning is valid, at least, to the case-study company of Section 3.2.2, which started implementing isolated lean practices by its own initiative, but then stablished an integrated and structured lean program as a consequence (and requisite) of their involvement with their automotive customers. Although some initial setbacks were perceived by the staff and the required cultural change took several years, after approximately 6 years of LM implementation, the acceptance of new practices began to "smooth", and the company management started pursuing improvements in some environmental and social indicators, profiting from some of the perceived benefits of lean. Some of said environmental benefits (in the form of 3Rs programs) have been already discussed in the previous section. Also, signs of positive social outcomes were evidenced in the form of improved employee motivation. While interviewing operators of the company, the ones which have had most time applying lean practices said that "*we have achieved very good results. In the beginning, it was difficult to change, but after a while, we realize that this lean "thing" really works*"[16].

[16] Translation from the remarks of one operator-level employee of the case study company.

Also, while interviewing tactical-level employees, it emerged that many of them had previously worked in other companies that had successful lean implementations, and they felt that the knowledge of lean tools was highly regarded in the local work-market, which relates lean to a higher job security perception (another social performance indicator). To further support this point, a simple study was conducted. Job offers related to "manufacturing" operations were searched using LinkedIn social network. The offers were then filtered to show only full-time offers, in companies located in Colombia. A total of 361 job offers were found, ranging from machine operators to plant and operations managers. Interestingly, knowledge of lean manufacturing, six sigma, or other continuous improvement practices was required in more than 70% of the cases, and especially in almost all management positions offered. This effectively suggests that lean abilities have become highly valued in manufacturing industry employees (at all company levels), and people with lean knowledge can have better leverage to negotiate improved working conditions that could reflect in some social indicators as improved salary, or non-economic compensations.

In this line of reasoning there are some evident benefits of LM on sustainable performance and all its TBL dimensions, which are supported by the results of Figure 40, Figure 41, Figure 42, and Figure 43. However, it also seems that direct effects of lean are more evident at operational level but become more marginal when looking into environmental and social level outcomes. This reasoning is consequent with some results of previous research, which failed to fully support (or did not found) effects of LM on some TBL pillars, when evaluating those simultaneously, but as individual constructs for each dimension (in contrast to the employed approach in Figure 43). For example, Varela et al. (2019) found that for their sample, the effects of LM on each one of the TBL pillars were not statistically significant, and therefore, neglectable. Resta et al. (2016) found no significant effects of LM on environmental performance, and positive effects on social performance only in some cases, while de Freitas et al. (2017) found no effects on social indicators. Interestingly, the most recent study from Chavez et al. (2020), did not manage to support significant effects of LM on operational performance (when considering it simultaneously to the other performance dimensions).

The discussed results (from this research and other previous ones), point to complex interactions between all sustainability pillars (Cherrafi et al., 2016), that are affected in different ways by lean manufacturing, and seem to be also severely influenced by other external variables, such as, company size, age of lean program, market sector, or even socio-geographic context. Therefore, results in literature change in unexpected ways, ranging from positive to negative effects of LM on each TBL pillar, depending also on which indicators were used to measure each construct. In spite of this, there seems to be growing evidence pointing to the conclusion that, in general, lean manufacturing does have positive effects on sustainable performance (as also supported by the results of this research), but a larger debate remains around the nature of such interactions and the critical success factors that make the difference between positive and negative results.

4.1.3. Cumulative approach to sustainability

As the debate regarding the effect of LM on sustainability continues to close towards a positive interaction, the main objective of this research was to provide insights on which was the correct path to ensure that said positive relationship materializes. Hence, two approaches were proposed. First a cumulative approach (hypothesis 1), on which sustainable performance is "built" on the basis of a solid operational performance (driven by the implementation of LM), that allows to place environmental benefits on top of it, and finally, to obtain social performance improvements as a consequence. This approach resembles the sand-cone framework proposed by Ferdows and De Meyer (1990) and Schroeder et al. (2011), although it represents a novel contribution from the present research as it is the first time (to the authors knowledge) that said approach has been proposed and proven in the context of sustainable performance. The second proposed approach consists of a trade-offs model (hypothesis 2), which poses that at high levels of lean manufacturing implementation the resources needed to drive performance improvements on each TBL pillar will begin to clash with each other, inevitably leading to one performance dimension being privileged over the others.

The results on Section 3.6.5 provide strong evidence to accept hypothesis 1. According to Figure 44, there is a sequence of significant positive effects that goes from LM to OPR, then ENV and finally SOC, thus showing that a cumulative performance "sand-cone" is present in the sample. The positive and strong standardized effect of LM on operational performance (0,78; $p<0,001$) was expected from the general consensus of literature which highlight several evidences of such relationship. Then, "green spillovers" from lean manufacturing have been identified in some cases (although no concluding evidence is present in literature), which gave some grounds to expect the positive effects on environmental performance derived from the improvements on operational performance (0,36; $p<0,05$). Finally, with social outcomes being the less studied of the TBL pillars, the results were more hardly to foresee, and they could be expected to range from positive to negative, as it has been the case of the few studies that have aborded the matter on literature. However, the obtained results show that there is also a significant positive effect of environmental performance on social performance (in the presence of LM) (0,41; $p<0,01$), and give support to suggestions that a cleaner work environment achieved through the implementation of lean practices positively reflects on social indicators such as, health and safety and employee motivation (Longoni et al., 2013; Souza et al., 2018).

Although the line of reasoning behind the cumulative approach proven on hypothesis 1 might seem straightforward, this is the first time that empirical evidence is provided for this approach. In a practical manner (and drawing from theoretical backgrounds on both lean and sustainability), the obtained results suggest that the higher the level of lean manufacturing implementation, the higher the improvements on operational performance that can be perceived on variables such as cost, quality, production lead-time, cycle time (manufacturing cadence), and work in process inventory.

This is because lean practices (and lean as a complete "philosophy") were precisely designed to impact said performance variables. TPM and SMED practices (associated with the technology construct) enhance productivity, diminish process downtimes, and increment OEE, which in turn reflects in lower manufacturing costs and higher output (lower cycle time). Then, all the practices and goals pursued by the quality construct (SPC, customer feedback, etc.) are, off course, expected to lead to lower rejection and rework rates, and fewer customer complaints. The use of pull systems, both for production planning and supply, as well as a continuous, demand-driven, process flow helps to reduce the required WIP and lead-time. Finally, a long-term supplier development program can result expensive at the beginning, but materializes in a reliable and competitive supply chain, that will reduce costs, lead-times, and ensure a sustained quality.

The abovementioned benefits on performance are hard to achieve without the use of base-line practices which are related to the HRM construct (Bortolotti, Boscari, et al., 2015; Jabbour et al., 2013; Vivares-Vergara et al., 2016), and off course, without management commitment (Alefari et al., 2017; Netland, 2016; Vinodh, Ramesh, et al., 2016). In turn, direct gains on all performance variables can be expected as a result of a continuous improvement culture (*Kaizen*), as well as lower defect rates and cycle times that can be expected from cross-training and standardized processes. All said benefits comprise the base of the “sustainability sand-cone” that can be achieved through lean manufacturing.

Then, for the second layer of the sand-cone, interesting relationships begin to arise. It is expected that a good operational performance contributes to a good economic performance. It has been suggested that companies with sound economic performance have more resources available to invest in environmental and social programs (Sadeghi et al., 2016; Wang, Lu, et al., 2016). This is supported by the obtained results of Figure 44, with environmental improvements being reflected in a reduction of the use of hazardous materials in production process, reduction of solid-waste generation, reduction of green-house gas emissions, and environmental regulation compliance. A naturally expected effect is that of 5S implementation on the reduction of waste and emissions, derived from a cleaner work environment. Improved quality means lower rejection rates, that also reflects in less waste generation. This findings are consequent with those of Solaimani and Sedighi (2020) who call the effects of lean principles on TBL dimensions “reinforcing”, although their study was conducted in the context of construction industry.

On the other hand, other less direct effects of lean practices can also materialize on environmental improvements. A generalized continuous improvement culture, in addition to employee empowerment is not likely to stop with employees trying to improve operational conditions. Instead, it is likely to be a fertile ground for employees to start looking for ways to improve their processes and products that could result in less use of hazardous materials, and improvements in all other environmental variables. VSM practices could help to identify operations that unnecessarily consume resources (or generate waste), and the discipline and transformation of the organizational culture required to achieve a successful lean implementation, will help to embrace environmental practices and facilitate taking actions to improve regulatory compliance. Finally, a management committed to a lean program, is more likely to continue allocating resources to environmental and social programs after being reassured that their lean “investment” has effectively materialized in tangible performance gains.

A worth noticing caveat is that increased cadence and the reduction of lot sizes (both in supply and manufacture) have been related to higher energy consumption rates in the form of increase transportation of materials, and the energy required by the machinery to run at higher rates (Bergenwall et al., 2012; Fahimnia et al., 2015). This could explain why the reduction on energy consumption item presented a low factor loading during the CFA in Section 3.5.3, and had to be excluded from the environmental performance construct. Nevertheless, it could be expected that the gains on all other environmental performance items outweighs the possible detriments in energy consumption.

The top layer of the sand-cone is comprised by social performance, as the significant positive effects of environmental performance demonstrate. While multiple calls have been made in literature to address the social outcomes of manufacturing operations, as well as its interactions with the other two pillars of sustainability, empirical evidence to clear those questions remain scarce. This marks another notable contribution of this research, as it gives light of how social variables such as wages and economic compensation, new direct and formal workplaces creation, employee turnover rate, and employee satisfaction and motivation, can be improved in the presence of LM.

As Figure 44 shows, the direct effects of LM on SOC are not statistically significant, therefore, the improvements in social performance present in the data sample came as an indirect consequence of lean, and as a direct consequence of operational and environmental gains. As in the case of environmental practices and programs, it is foreseeable that a strong management commitment to a successful lean program could easily be extended to support other programs and practices with a social and worker welfare orientation (Awan, 2019). Also, an improvement culture, periodic training, and empowerment of employees, can reflect in an increase of their satisfaction and motivation, while cross-training programs can help to prevent employee turnover, as workers develop multiple skills that allow the company to redirect them to other processes in the event of a product end of lifecycle or lower demand.

Most evident, as it was previously stated, a sound operational performance achieved with the help of lean manufacturing drives down costs, improves quality, decreases lead times, and WIP inventories. Those benefits, in turn, can reflect in better market and financial performance, through more competitive and available products, improved customer satisfaction, and less capital trapped working capital, therefore leading to a higher business performance. A growing company, with high levels of business performance, generally has a growing demand for its products, which materializes in more required workplaces, and usually, with better economic and non-economic compensation in order to attract new employees to support its growth.

There are also direct effects of improved environmental performance that can translate into social gains, as the result revealed. For example, the reduction in use of hazardous materials can improve health and safety, as the reduction of noise and pollution can improve worker satisfaction. Finally, it can be argued that improved compliance with regulatory standards should prevent the company of being sanctioned (or even closed) by the authorities, which also reflects in an increased sensation of job security.

In consequence, the cumulative approach in which lean manufacturing improves sustainable performance following a sequential improvement of operational, environmental and social indicators, has been supported by the obtained results. Said results constitute an important contribution as it is the first time that this cumulative relationship has been proposed and empirically proven in the context of LM and sustainability and shed light of the interactions between the three TBL pillars. The achieved results are sound in their logical, practical, and theoretical grounds, which suggest that they indeed reflect a real-world cause-effect relationship among the studied variables, instead of being produced by chance, and therefore, help to enrichen the theoretical knowledge surrounding both the lean manufacturing and sustainability fields of study.

4.1.4. Trade-offs approach to sustainability

Trade-offs between sustainability pillars have been suggested in literature, especially in the last decade (Figge and Hahn, 2012; Kravchenko et al., 2020; Orjuela-Castro et al., 2019; Pagell and

Shevchenko, 2014), however, this represents the first time (to the author knowledge) that trade-offs between all TBL pillars are assessed simultaneously, and, that the influence of manufacturing strategies (in this case LM) that requires a fair commitment of resources on said compromises has been tested and proved.

Evidence to support the second hypothesis (a trade-offs approach) was not entirely conclusive on the results. The model on Figure 45 proved to be unstable, which forbid it to prove the existence of trade-offs among all TBL pillars. This result could come as a consequence of hypothesis 2 being false (i.e., there are no trade-offs among TBL pillars in the presence of LM), or it could also be a result of methodological issues. Non-recursive SEM models (as the one on Figure 45) have complex bidirectional connections that create infinite cause-effect relationships (Gempp and González-Carrasco, 2021). When said relationships are well defined in the data sample, they converge to a proper set of estimated parameters that pose an acceptable fit between the implied correlations of the model to those present on the real data (what is called an “stable” model). However, the achievement of said convergence can be highly affected by the sample size and the number of non-recursive paths present in the model.

Although the sample size available for the present research is considered appropriate in light of the studied constructs, items, and regression paths (as discussed in Section 3.5.4), there is scarce information regarding appropriate sample size for the case of non-recursive models. Therefore, the stability of the model presented in Figure 45 could have been affected by the sample size. It is also worth mentioning that there are three non-recursive relationships present in said model, which is also a factor that can be affecting model stability and preventing the convergence of parameter estimates. Hence, it is difficult to tell why the trade-offs model did not proved to be correct, however, it can be concluded that no evidence of simultaneous trade-offs between all pillars of TBL were found, at least, for the available sample.

However, on the grounds of the alternative models tested in Figure 46, Figure 47, and Figure 48, the trade-offs hypothesis cannot be completely rejected. At least two of the alternative models showed evidence of compromises between pillars of TBL performance. Figure 47 shows a positive effect of LM on all TBL pillars, however, while the standardized effect of SOC on OPR is positive (0,55; $p<0,001$), the reciprocate effect of OPR on SOC is negative (-0,71; $p<0,005$) and larger in magnitude. Giving a lecture to said result is complex as there could be a significant number of external variables conditioning the results. However, given that the regression weights on the model are statistically significant and relatively large, there is a substantial influence of the lean manufacturing construct on the evidenced results.

A plausible explanation, based on propositions and theories found in literature is that, while lean manufacturing is capable of producing a positive direct effect on each TBL pillar separately (as it was already proven on Sections 3.6.1, 3.6.2, and 3.6.3), when the complex interrelations between all dimensions of sustainability, and the indirect effects of LM, are accounted for, trade-offs become apparent. If the path form LM to SOC to OPR is followed, both the direct, indirect, and total effects are positive and statistically significant, as Table 57 evidence. Therefore, it can be said, that LM has positive direct impacts on social performance, which have been discussed in previous sections, and are mainly reflected in employee satisfaction and motivation, as a consequence of training and empowerment. In turn, said social benefits have the capacity to positively impact some operational measures (Chavez et al., 2020). It has been argued that motivated employees are more productive, therefore, a reduction in cycle times and reject rates can be expected. Also, empowered employees are prone to solve day-to-day production problems quickly, without the need of their supervisors in most cases, which should also reflect in better costs and product quality (Resta et al., 2017).

However, when the relationships are evaluated following the LM to OPR to SOC path, the effect of LM on operational performance is still positive (as expected), but the effect of operational performance on social performance becomes negative. The indirect effect of LM on SOC (through OPR) becomes also negative, meaning that the operational performance gains derived from lean manufacturing implementation have detrimental effects on social performance. In this case, it can be argued that, based on propositions by some authors, the initial introduction of some lean practices can create adverse effects on employees (Longoni et al., 2013; Resta et al., 2016), which manifest on additional pressures of cultural changes, changes of the work environment, and meeting of lean goals and deadlines. Also, the elimination of non-value-added operations from VSM practices, can lead to redundant workplaces and layoffs of no longer needed personnel (Manotas Duque and Rivera Cadavid, 2007). Bergenwall et al. (2012) also found that some employees are reluctant to cross training as they perceive less job security if their work abilities are developed by other personnel.

A similar behavior can be found when analyzing the model on Figure 48, were evidence of trade-offs manifest between environmental and social outcomes. In this case, the relationship is more complex, as the path from LM to ENV is statistically not significant, which is partially consistent with Resta et al. (2017), who found that, when considering all TBL pillars, some lean practices did not produce significant effects on environmental performance. Instead, the path from LM to SOC to ENV has positive effects, which in the case of LM→ENV were explained in Section 3.6.2. Also, evidence of positive effects of social performance on environmental performance have been suggested in literature. Chavez et al. (2020), found that satisfied employees are more committed to organizational goals, which include some green goals like reduction of emissions or compliance with environmental regulations. In addition, as it was the case of the SOC→OPR analysis, empowered employees are expected to solve environmental day-to-day problems in a more expedite way.

What becomes interesting is that the improvement in environmental performance has a detrimental effect on social performance (-0,87; *p<0,005*). There are less theoretical grounds on literature to explain this relationship. However, a possible explanation is that a company might allocate resources for LM implementation, that initially generate improvements in social outcomes. Said social outcomes can be translated into environmental performance gains with the allocation of more resources focused on the implementation of complimentary green practices. Also, it is known that as environmental regulations become stricter, the initial costs required to meet them increases (Danese et al., 2019; Gupta, 2016; Porter and van der Linde, 1995). At that point, the required resources begin to clash between the requirements of LM, social programs, and green practices, which ultimately reflect on the negative ENV→SOC effect.

Table 57. Lean manufacturing standardized direct, indirect, and total effects on sustainability pillars

Model	Direct effect			Indirect effect			Total effect		
	LM→OPR	**LM→ENV**	**LM→SOC**	**LM→OPR**	**LM→ENV**	**LM→SOC**	**LM→OPR**	**LM→ENV**	**LM→SOC**
Figure 47	0,526[b]	0,571[a]	1,011[a]	0,252[a]	-	-0,552[b]	0,779[a]	0,571[a]	0,460[b]
Figure 48	0,788[b]	0,158[c]	0,969[a]	-	0,407[a]	-0,490[b]	0,788[b]	0,566[a]	0,478[b]
[a]*p<0,001*; [b]*p<0,01*; [c]*not significant*									

In both evidenced cases of trade-offs, those occurred with the social performance dimensions of sustainability, indicating that this TBL pillar is the more sensitive to receive negative influences from the other two pillars. Given the right conditions, it should be expected that a higher operational and environmental performance lead to improvements in social performance, as it was proven in hypothesis 1. However, the right sequence of performance improvements must be applied, in order to achieve cumulative gains, rather than having concurrent social, environmental and operational goals that compete for resources in a lean manufacturing implementation environment that is, by defect, highly demanding on organizational resources.

Therefore, it can be said that one of the main factors for the development of trade-offs between TBL pillars during LM implementation is the clash of resources. LM implementation require high levels of management commitment and the allocation of enough resources to do so (Alefari et al., 2017; Vinodh, Ramesh, et al., 2016), especially if performance improvements are not only expected at operational level, but also on environmental and social outcomes (Awan, 2019). In addition, the initial phases of lean implementation can put an organization under significant stress because of the cultural changes required, and the demand of not only economic resources, but also of the employees time and attention (Čiarnienė and Vienažindienė, 2014), while they still have to attend to their day-to-day obligations.

In this scenario, when a company pushes for simultaneous performance gains on all TBL dimensions while implementing LM, it risks overloading their productive system and their workforce, who could become demotivated, and decline its performance. Also, lean programs can take several years to start rendering positive results (Burawat, 2019; Grigg et al., 2020; Sadiq et al., 2021), and impacts on some external social measures can take even longer to materialize (Henao et al., 2021). Therefore, an initial decay on some (or all) performance dimensions can be expected, as a consequence of the required resources exceeding the perceived benefits (Wang, Lu, et al., 2016; Younis et al., 2016). Hence, this situation manifests itself in the evidenced trade-offs among TBL pillars. Said trade-offs could be overcome after some time, if commitment is retained for long enough to start providing tangible benefits from lean, green, and social programs, or could turn into a vicious circle in which, performance gains in one dimension are constantly overshadowed by losses in other.

Finally, when factoring the total effects of lean manufacturing on each TBL pillar (see Table 57), they all become positive and statistically significant. This suggest that although trade-offs can be present among the different sustainability pillars (especially with the social pillar), in the end, the effect of lean manufacturing on each TBL dimension is still positive, as all the previous sections had suggested. However, what can be concluded is that in this case, trade-offs will still be present, which could become difficult for companies to handle in their short-term decision making processes, as it can be hard to identify which adverse performance results (mainly in the social dimension) are transitory trade-offs derived from lean implementation, which however are expected to result in long-term benefits, and which ones are a consequence of structural company problems that require boing addressed in a different manner, as they risk to become long-term sustainable performance handicaps.

4.1.5. Final discussion

There was strong evidence to support the cumulative approach to sustainable performance (hypothesis 1). In the case of the trade-offs approach, there was partial evidence. These results, although did not fully support hypothesis 2 (that trade-offs occur between all sustainability pillars), have clear indicators that trade-offs are present between the social pillar of TBL, and the other two, but only when evaluated separately. Both results constitute a noticeable contribution of this research, as it is the first time (to the author knowledge) that empirical evidence has been provided to support both the cumulative approach and the trade-offs approach in the context of the effects of lean manufacturing on sustainability.

The aforementioned results might sound contradictory at first glance. In fact, when Ferdows and De Meyer (1990) proposed the sand-cone approach they suggested it as an alternative to facing trade-offs between manufacturing capabilities (i.e. cost, flexibility, dependability, quality, etc.). In the last three decades, OM literature has been marked by both approaches with two simple propositions. Under the first proposition, companies can specialize in one manufacturing capability and develop high levels of competitiveness leaning on being strong in a particular characteristic, at the expense of the others. Under this approach it is better to be exceptional on one single competitive aspect, like cost, or quality, instead of being average in everything. In contrast, under the second proposition a company can develop manufacturing capabilities sequentially, meaning that, the improvements in one capability will settle the grounds for subsequent improvements on others.

Extending the above propositions to sustainability, it can be said that a company can concentrate on achieving exceptional results on one single dimension of sustainability, and focus all its resources on the chosen direction, at the expense of sub-par performance in the other two, thus employing the trade-offs approach. The alternative (i.e., the cumulative approach), is to start building performance improvements in one dimension, that will be used as a platform to improve performance in another dimension later, and so on. In the case of OM, the debate regarding which one is the appropriate approach is still ongoing in literature. In the case of sustainability, the topic is still relatively new, therefore, it is still in an exploratory phase, where empirical grounds for both theories are yet being researched and developed. In this sense, the results of this research provide a valuable contribution to the field of study.

When conducting a more profound analysis, in light of the variables involved, the present research results from both approaches starts looking complementary, instead of contradictory. This proposition has grounds when dealing with manufacturing capabilities, with Ferdows and De Meyer (1990) noticing that "*depending on the approach taken for developing each capability, the nature of the trade-offs change. In certain cases, not only can trade-offs be avoided altogether, but in fact one capability would enhance another. They become cumulative. Moreover, when a capability is developed in this way, it is likely to be more lasting and less fragile than if it were developed at the expense of other capabilities*".

The key to Ferdows and De Meyer (1990) findings (latter supported by Schroeder et al. (2011) and many other authors), when extending the premises to sustainability, is precisely marked by the phrase "*it is likely to be more lasting*". Regarding sustainable development and sustainable performance, thinking of a single dimension of performance being privileged at the expense of the others contraries the foundations of Elkington's (1998) triple bottom-line approach to sustainability. Sustainability has to be envisaged as a long-term goal, therefore, it is unlikely to expect that in a globalized world, with ever-growing concerns and pressure from multiple stakeholders to address social and environmental outcomes (Chen et al., 2020), a company can last in time focusing only on operational/economic bottom-line results, disregarding their impacts on society and environment. The same can be said from a company with outstanding environmental performance, but without concerns of their impacts on its workers and community, or vice versa. Finally, a manufacturing company is also unlikely to maintain its operations if operational and economic expectations from its shareholders are not met.

In this context, for companies to succeed in the long term under a TBL approach, all sustainability pillars must be embraced equally, however, there is no magic recipe to achieve that, and, although sustainability research in manufacturing operations has provided a few frameworks for sustainable manufacturing, none of them has sufficient empirical support to make it outstanding among the others. This is where lean manufacturing presents itself as an interesting way to achieve sustainability goals, when combined with the main contributions from this research. The obtained results provide a pathway to extract performance improvements on all TBL dimensions as a consequence of LM implementation.

According to the results, a concurrent (i.e., simultaneous) focused on implementation of lean manufacturing while pursuing performance improvements on all TBL dimensions, is likely to render undesirable short-term results, which manifest in trade-offs that are mostly harmful to social performance. It is unlikely, that in such scenario, enough resources (time, money, personnel, attention, etc.) can be allocated to all required social, green, and lean programs, resulting in a situation that can even be detrimental to multiple (or all) performance dimensions. Said phenomenon is also prone to manifest in early stages of lean adoption when there has been not enough time for performance improvements to become tangible. Instead, a sequential approach (the cumulative or sand-cone approach) is more likely to boost performance in all TBL pillars.

The results suggest that the path to achieve such sustainable improvements follows a straightforward logic. A proper implementation of LM is expected to achieve what it was originally designed for: the improvement of operational level variables. Along with said improvements some green and social “spillovers” (i.e. positive side-effects) could appear. Along with discipline, cultural changes, momentum, and more importantly, results that ensure continuous management commitment, the operational gains of lean, serve as a platform for other initiatives that could produce a more direct impact on environmental performance, thus, creating the second layer of the sand-cone. Finally, operational and environmental gains would enhance social performance. Most like a real sand-cone, the taller the cone gets, also the wider its base layer (and subsequent layers) grows. This means that (although not directly tested in the hypothesized models) it is likely that the sustainable performance sand-cone turns into a virtuous circle, where, improved social performance also positively affects operational performance (motivated employees are more productive, and companies with high social reputation tend to have better market performance), resulting on more green gains, and so on.

4.2. Theoretical and research implications

This research presented a novel approach on which two well-known theoretical frameworks in the field of operations management (the trade-offs and the sand-cone) were extended to the field of sustainability to evaluate the effects of lean manufacturing on triple bottom-line performance. The proposed models for development of sustainability on manufacturing (specifically metalworking) operations open new pathways for research on both approaches that should lead to better understanding of the situations and variables influencing each approach, and ultimately lead to a more comprehensive development of theoretical frameworks around the sustainability sand-cone, and the TBL trade-offs.

The obtained results contribute to closing many knowledge gaps evidenced in the state-of-the art literature. While the effect of lean manufacturing on operational performance are considered a fairly closed debate in scientific literature (there is strong consensus supporting a positive effect), the debate is still open regarding environmental performance and especially social performance. One of the theories involving LM and environmental outcomes is that of the “green spillovers”, which claims that most environmental benefits derived from lean are only side-effects (Piercy and Rich, 2015; Resta et al., 2016). The results of this research contributes with proofs of said green spillovers, giving empirical grounds to that theoretical approach. What is more important is that evidence of “social spillovers” were also found in the results. Although some authors had previously tacitly suggested some positive side-effects of lean manufacturing on social variables, it is the first time (at least in the reviewed literature) that such social spillovers are explicitly evidenced.

From the LM implementation perspective, the obtained results support the contingency theory proposed by many authors such as Chavez et al. (2015), Fullerton et al. (2014), Netland (2016), and Sunder and Prashar (2020). Under this theoretical perspective, the “one approach fits all” LM implementation is likely to fail (Danese et al., 2018). Instead, companies should adapt their lean approach in accordance with their context, culture, and strategy, ensuring a less stressful lean transition and more sustainable results. The results suggest that indeed cultural, geographic, and even language barriers are among the CSF for lean, and evidence was found on the case study that companies tend to achieve better results from lean practices that are highly adapted, rather than implementing them “by the book”.

In this line of thinking, the proposed approach to lean assessment based on the efforts done by companies to pursue lean goals and principles, rather than measuring “standard” lean tools and practices, provides an interesting framework for future research. Most survey-based empirical research on LM to date follows the “bundles” approach originally proposed by Shah and Ward (2003), which is however prone to context, cultural and language biases, as it struggles to take into account the adaptations done by companies to their lean practices. Instead, it can be argued, that the method employed in this research favors a more universal assessment, which is consistent with previous propositions by Nawanir et al. (2018) and Oleghe and Salonitis (2016).

The results open some paths for research along novel theoretical basis that are still in an early stage of research. While sustainability research has reached a mature stage where some solid theoretical frameworks have been developed in the last years, and everyday more empirical evidence is being collected to support those frameworks, the research in sustainable manufacturing is still somehow relegated to a theory-development stage. When the effects of lean manufacturing are taken into account in said sustainability frameworks, there are still several knowledge gaps to be filled, starting with a clear and decisive understanding of the answer to the question: does lean manufacturing improves sustainable performance?. In the light of the results of this research, the answer should be yes (at least in the context of the studied object), a notion that is partially shared with other recent studies (Chavez et al., 2020; Sajan et al., 2017; Solaimani and Sedighi, 2020), even though said studies were conducted in different sectors, contexts, or countries. Although this represents a valuable contribution, other theoretical approaches suggested in literature point to less conclusive answers or even to the contrary. This contrasting behavior is however expected at the current state of lean-sustainability research, which is still on its infancy (de Freitas et al., 2017; Martínez León and Calvo-Amodio, 2017).

The TBL approach proposed by Elkington (1994) has become one of the dominant theoretical paradigms in sustainability (at least regarding manufacturing operations), given its practical approach and its win-win-win balance between sustainability pillars. However, empirical evidence to support said theoretical win-win-win environment remains scarce, and sometimes even contradictory. The obtained results suggest that, given the right conditions (including a clear management commitment to continuous improvement and sustainable performance), this scenario is achievable in practice, avoiding undesirable trade-offs among TBL dimensions that have been evidenced in other contexts or sectors (Orjuela-Castro et al., 2019; Solaimani et al., 2021; Stindt, 2017).

Therefore, one of the main theoretical contributions of this research was to provide explanations, and proofs, of the sequential improvement of TBL dimensions (the sand-cone approach) that could materialize in a positive effect of LM on sustainability. Also, empirical evidence is provided (along with explanations) for the case on which the performance improvements fail to materialize on all TBL dimensions, thus, resulting on trade-offs. This contributes to answer a constant call in recent literature to conduct more empirical research aimed at understanding the critical success factors (and critical failure factors) for the implementation of lean manufacturing, and more importantly, for achieving the expected benefits on each performance dimension.

Finally, this research contributes to the field of knowledge by suggesting two assessment instruments for the variables involved (lean manufacturing implementation level and sustainable performance), that are derived from current theories in both fields and the state-of-the-art literature. Empirical validation of both instruments was performed through expert's analysis, PCA and CFA, which gives reliability and validity to them. Both instruments could be useful for other researchers to conduct further research on lean manufacturing or sustainable performance in manufacturing organizations. Moreover, given that the proposed lean instrument is based on generic lean goals that should be valid in almost all manufacturing contexts, and the variables selected for the assessment of each dimension of TBL performance are not related to local regulations or specific reporting frameworks, both instruments are highly likely to be valid in other industrial contexts or in other countries.

4.3. Managerial and practical implications

The research results offer a series of practical implications that could result helpful for managers and consultors in different kinds of manufacturing companies. Companies and process managers implementing lean should avoid many "lean myths" that had developed over time and that could result in an unsuccessful lean program. First, there is not a universal recipe for implementing lean. Many books and consultants suggest step by step approaches to lean practices that are supposed to guarantee performance improvements on a short term. Said guidelines are no doubt helpful, but their success depends not necessarily on doing things by the letter. Instead, recent lean research points to companies needing to be aware of the lean goals that they are pursuing, how they can be integrated with their company strategy, and how committed they are to becoming a lean company.

In fact, many lean failures can be traced to misalignments between the firm strategy and its manufacturing strategy. For example, companies trying to implement a fast market strategy (i.e., take profit from newly developed technologies before other competitors arrive) are more likely to obtain benefits from agile manufacturing paradigms than from lean. Another example is present in large process-oriented factories (as it is often the case of the petrochemical industry, and other primary industries), where the whole production scheme is centered around maximizing output of a single product without major concerns for flexibility. In this case, while some isolated lean practices can provide some performance improvements, it is likely that an integral lean program can clash with the intrinsic process limitations and the outright company strategy.

The results obtained through several stages of this research support the above claims. First, management commitment was found to be one of the main lean constructs while reviewing state of the art literature, with many lean implementation indicators relating to it. Second, this was validated by the consulted experts which concluded that the alignment of manufacturing strategy (including lean) with organizational strategy, a top management driven 5S culture, a continuous effort to map and minimize non-value-added activities, and the commitment of resources for lean implementation and a close follow-up of the results, are clear and relevant indicators of management commitment to successful lean program.

In addition, the results of the case study performed during the research, revealed that the “one approach fits all” implementation method commonly employed by massive lean programs sponsored by customer companies (as was the case of the Colombian automotive manufacturers), government agencies, or some consultants, can clash with the particularities of each company goals, processes, and culture. Instead, the results showed that the lean practices that were adapted (instead of being taken “by the book”) were the ones that offered the better perceived results by the company personnel. This represents an important implication, especially for managers of SMEs, since they often won’t have enough resources to fully commit to a lean program. Instead, most SMEs rely on externally founded programs to implement LM (Grigg et al., 2020). Therefore, managers should be aware that following strictly an external lean implementation program does not necessarily guarantee a positive impact in performance or its sustainability over time.

This contributes to the ongoing debate in literature regarding the approach to lean manufacturing as a series of bundles of practices and tools, each one aligned to a specific lean construct or pillar, or, in the other case, as an integrated philosophy centered around some lean principles and goals regardless of the practices employed. While measuring the lean implementation level, this research employed the second approach for practical purposes, like avoiding language barriers and inter-industry differences in the applied practices. However, concerning a practical lean implementation, it must be said that the better results are likely to come from a conscious combination of both approaches.

The results suggest that it is crucial that a company willing to implement a complete and successful lean manufacturing program has to be able to visualize lean as an integrated philosophy, be aware of its principles, and make sure that the lean goals are relevant and consequent with their organizational goals. This becomes crucial to withstand (and willingly face) the cultural changes required to implement a long-term lean journey, not only at the manufacturing or plant-floor level, but at an organizational level, as the lean commitment goes beyond those dimensions and has an impact on human resources, logistics, supply, and even sales and financial company functions. Then, after making sure that there is a strong apprehension of lean principles, and willingness to pursue lean goals, the organization will have a share of practices and tools available to achieve said goals. The company can choose the tools that best fit their interests and their approach to lean and will have to make adaptations to make them useful in their technological and cultural context.

In a similar way, there is no universal pre-defined script to achieve sustainable development. In manufacturing operations, some frameworks have been proposed to improve performance on each TBL dimension, however, their implementation presents no guarantee that said improvements will materialize, especially, when the interactions between the operational, environmental, and social outcomes are accounted simultaneously. In this context, the results of this research are useful to managers and practitioners as they provide guidelines of what to do (and what not to do) when pursuing sustainability improvements in manufacturing operations.

As the results show, the implementation of lean manufacturing can be a powerful tool to boost sustainable performance, but only if the right sequence is followed and the company is prepared to allocate the required resources at the right time. Unless there are exceptional circumstances, that include a large investment of organizational resources (people, time, and money, among others) and a decisive focus, a simultaneous implementation of lean manufacturing with performance enhancing pushes on all three TBL pillars is likely to result on trade-offs detrimental mainly of the social dimension. Instead, if managers opt for a more conservative long-term approach to lean implementation, sequential performance improvements can be achieved in the operational dimension, that in turn will support further improvements on the environmental and social dimensions. This is the proposed “sand-cone” approach to sustainability, that constitutes a helpful instrument for companies when defining their sustainability-oriented strategies.

Another worth noticing practical implication of the obtained results is that they should be useful for government institutions to develop and promote public policies that help Colombian companies improve their competitiveness in a challenging globalized environment, while meeting worldwide stakeholders’ expectations of sustainable development. It is important to mention that during the course of the research, links with many local chambers of commerce, industrial guilds, government agencies to promote industrial development, manufacturing companies, and other universities were established. All those actors showed interest in the researched topics and are willing to exploit the results developing courses, guidelines, lean and sustainability programs, mentoring, and other useful instruments for local companies.

Following the last paragraph, it is also important to mention that all companies participating in the research (when a valid e-mail address was provided in the questionnaire) were provided with feedback and recommendations regarding their results. It was important to maintain confidentiality, so no sensible information from any other company was shared. Instead, the generic report sent to each company presented the results obtained by each company on each one of the lean constructs and sustainable performance constructs relative to the overall sample (i.e., each company was let known on which percentile of the results it sits). Then, based on the reviewed state-of-the-art literature, the research results, and the conclusions, a series of guidelines for lean implementation, and sustainable performance improvement were developed and sent to each company according to their relative results.

Finally, while it was not the intention of this research, and no statistical or methodic tests were followed to support the following comments, it is the author perception that personnel with knowledge and "hands on" experience on lean manufacturing implementation are becoming highly regarded in the context of Colombian industries. Many of the experts and companies' employees reached through the course of this research feel that Colombian companies are willing to attract "lean employees" with higher salaries, higher positions, and other benefits. This suggests that companies' managers are aware of the benefits of lean manufacturing and are willing to invest in more expedite lean implementations through the experience acquired by other companies. This is an interesting practical implication for all manufacturing companies' employees (regardless of if they have an operational, tactical, or management role), since it can become a motivation to actively participate in their companies lean programs and trainings, as it is also an interest implication for universities, as there is a growing demand to include lean courses in their engineering pensums, and lean trainings and courses in their professional development offers.

4.4. Final conclusions

The sustainability debate (i.e. how to achieve sustainable development) is still far from being closed in operations management and manufacturing fields. More research is needed both for theoretical purposes (to develop new theories or expand current theoretical frameworks) and for empirical purposes (to test such theories and learn practical lessons from them). Although many have declared sustainability as a "race against the clock" for humanity in order to continue with human development in a technological, globalized, and resource hungry society, growing consciousness about the negative outcomes of human activities in the environment (and the society itself) is being achieved in the last years. Considering that the manufacturing industry is responsible worldwide for producing goods that in some cases are essential to modern subsistence, and along with that provides employment for a large portion of the world population, it is also important to notice that it contributes substantially to pollution, emissions, energy consumption, and waste generation. The results from this research contribute to help closing the gaps between the current state of environmentally harmful manufacturing (that in higher or lesser levels is present worldwide) and the expected state of fully sustainable manufacturing.

The triple bottom-line approach has played a crucial role in the development and implementation of sustainable manufacturing frameworks. While multiple sustainability and sustainable development frameworks have been proposed in recent years, like the United Nations Sustainable Development Goals (see Figure 22), they are often too general or too abstract for companies to implement in their day-to-day operations and decision-making processes. Instead, the TBL approach provides a concrete focus on measurable goals divided on three main pillars: economic (operational, when dealing with internal manufacturing measures) grow, environmental protection, and social development. In this way, manufacturing companies can select which goals to pursue and which indicators to follow on each TBL pillar according to their specific needs. While there is no guarantee that the TBL approach leads to long term sustainability, companies monitoring their performance on each pillar, and taking actions to keep a balance among them are more prone to achieve their long-term economic goals, while contributing to human development of their employees and the community, without causing detrimental impacts to the environment.

However, the task of pursuing and monitoring sustainable development in manufacturing organizations (and on all organizations) is a complex one. Among the many difficulties facing companies, there is the lack of sufficiently widespread, universal, and comparable sustainable performance measurement frameworks. There is no consensus regarding the appropriate level of sustainability that a company is expected to achieve and maintain. On one side, environmental and social legislations are different from one country to other, which creates a moral debate regarding the offshoring of manufacturing operations to countries with regulatory laxity. On the other side, although voluntary reporting frameworks (like GRI or KLD) have been around for some years now, most of the indicators are qualitative or subjective, and there is only relatively small amount of companies adhering to reporting initiatives, especially in developing countries.

To overcome the above problem, there has been many calls in literature to develop sustainability measurement frameworks that are practical, comparable, and useful to companies. Economic variables have been widely measured with universal indicators such as EBITDA, return on investment, or return on assets. Also, operational measures have a large battery of indicators that can be used for monitoring company performance (like OEE, unit production cost, reject rate, lead time, service level, etc.), and are also comparable among different companies, even regardless of the sector or country. However, when dealing with environmental and social indicators measurement, and more importantly, comparability becomes more difficult.

Most environmental indicators available tend to measure the level of harm done to the environment, as opposed to the level of “good”. Still, taking for example pollution levels, or toxic waste generation, not all companies use the same materials or generate de same by-products, hence the difficulty of them being comparable between companies. Finally in the case of social outcomes, external indicators are difficult to measure as they depend on information that is not necessarily available to the company. Also, some social effects of companies’ policies and programs are perceivable only in the long term, making direct, short-term impact social performance monitoring also difficult. In this context, an important contribution of this research is present in the set of variables proposed to assess the sustainable performance construct. Since the set of indicators was empirically validated using PCA and CFA, they could be adopted for monitoring sustainability improvements in all TBL pillars by Colombian manufacturing industries and could probably be also valid in other developing countries context. The indicator set is also a valuable contribution for academics and researchers requiring methods for quantifiable assessment of sustainable performance, which provide a certain level of inter-industry, inter-sector, or even inter-country comparability.

Regarding lean Manufacturing, it can be said that lean, as most manufacturing paradigms, was originally conceived to impact the economic and operational bottom-line of companies. However, the impacts and relationships between all manufacturing frameworks and sustainability. In the case of mass production, the dominant paradigm of the twentieth century, several negative on environmental and social outcomes have been document, mainly because it focus on the maximization of the production output, regardless of the resources required to drive higher production levels. With regard of its external outcomes (i.e. impacts outside the company), mass production depends highly on mass consumption and the consumerism culture, which has been criticized as one of the main contributors of global warming and non-renewal resources exhaustion of the last century.

By the end of the twentieth century, lean manufacturing began to establish itself as a world-leading manufacturing paradigm, replacing mass production in many companies. In the present century, it has probably become the dominant manufacturing paradigm worldwide, which in consequence has raised interest on its impacts on sustainability. According to many scholars, lean has the ability to provide many of the cost, quality and cycle-time operational benefits of mass production, without creating trade-offs with product and lot size flexibility, WIP inventories, and customization. This is thanks to a continuous improvement, flexibility, and quality focus that aims to extract the better from people, processes, and equipment. It has also been suggested that the implementation of a “lean culture” can take profit from this continuous improvement approach to create positive impacts on environmental and social measures.

Nonetheless, the effects of lean manufacturing on sustainable performance, and the question if lean is proper sustainable manufacturing paradigm, capable of continue driving industrial development for the years to come, while meeting the environmental and social expectations of global stakeholders, is a still going debate in academic circles, as well as around practitioners. Evidence of both positive and negative impacts of lean manufacturing have been found previously reported in literature, without a clear knowledge of the reasons behind said contradictory results. In this regard, the present research sheds an important contribution to the field of knowledge, as it is one of only few empirical studies that explores the interactions between LM and all TBL pillars, both individually and simultaneously. It also proposes, and tests, two approaches to achieve sustainable performance with lean manufacturing (the cumulative approach and the trade-offs approach), providing a valuable contribution on how the interactions between LM and TBL manifest in manufacturing companies, and delivering explanations for both the positive and negative effects on sustainability that can be expected when implementing lean.

It can be concluded that lean manufacturing has positive effects on each one of the TBL performance pillars (operational, environmental, and social). However, these effects are strong and direct only when each performance dimension is considered separately. Instead, when the complex interactions between all performance pillars are considered simultaneously, the effects on environmental and social performance become less representative (or even neglectable in the cumulative approach), leading to the conclusion that many social and environmental benefits that can be perceived after a successful implementation of lean manufacturing come as a side-effect of the improvements on operational performance. This reinforces previous suggestions in literature of what has been called “green spillovers” and is also one of few (if not the only) empirical evidence of “social spillovers” from lean.

If direct effects are expected simultaneously on all TBL performance pillars, it is likely that lean has to be integrated with other green and sustainable manufacturing paradigms. However, in such scenario, a vast amount of company resources are required at the same time, which could lead to a high risk of trade-offs between sustainability pillars. An important result from this research was the partial evidence of such trade-offs, which occur mainly in detriment of social performance. Therefore, it can be concluded that the resources required to simultaneously extract social, environmental, and operational benefits from lean manufacturing implementation are likely to result in short-term trade-offs.

To avoid such trade-offs, according to the empirical results of the tested models, it can be concluded that the most suitable path to obtain a comprehensive sustainable performance improvement form lean manufacturing is to follow a cumulative approach. In this way, lean manufacturing does what it was originally conceived to do: to improve operational performance. Those operational performance gains serve as a platform to support green initiatives, which profit from the management commitment, continuous improvement culture, and employee empowerment required to implement lean, along with the “green spillovers”. In turn, the operational improvements (especially those related to the manufacturing cost) are likely to free more resources to continue investing in social programs, which also benefit from a cleaner and healthier work environment, completing a sequential performance improvement that started with the positive effects of lean in operational performance, then helps improve environmental, and finally, social performance. This was called on this research the “sand-cone” approach.

To the author knowledge it is the first time that both the trade-offs and “sand-cone” approaches have been proposed, empirically tested, and proved in the context of the effects of lean manufacturing on sustainability. The obtained results from both approaches lead to the conclusion that the cumulative (sand-cone) approach, render better sustainable performance results than the trade-offs approach, which means that companies following the sand-cone approach are likely to develop cumulative improvements in TBL dimensions. This seems logical, as the trade-offs approach, by defect prioritizes one performance dimension above the others. What was not necessarily expected, and thus constitutes an important finding, is that under this approach, the improvements in operational and environmental performance are likely to create a negative effect on social performance. This initial negative effect could be expected to be mitigated somehow in the long-term by the total positive effects that LM is capable of produce on each TBL pillar.

Another worth noticing contribution of this research constitute the proposition and empirical validation of the lean manufacturing implementation level assessment tool. Although several lean assessment tools have been previously proposed in literature, and many of them have been used for empirical research purposes, the proposed approach in this research presents an evolution from traditional approaches previously employed, both in practical and academic fields. Common lean level evaluation tools rely on measuring the implementation of pre-defined sets of practices or tools that form “lean bundles” as proposed by Shah and Ward (2003). Said tools and bundles had evolved over time, and more importantly, have mutated to adapt themselves to different kinds of industries, stakeholder expectations, and socio-cultural contexts. Therefore, almost daily, companies worldwide adopt “new” lean practices and tools that can differ from the original set proposed by Shah and Ward or those developed by Toyota and other Japanese manufacturers in the second half of the twentieth century.

What has remained highly invariant over time are the core principles (or main objectives) of a lean production system (most of them described by Liker (2004)). In this context, the developed and proven lean assessment tool was based on measuring the efforts (and progress) that a company is doing to achieve a set of pre-defined (based on state-of-the-art literature) lean goals, regardless of any specific practice, method, or tool that it is employing. In this way, the assessment tool is less likely to be affected by language, cultural, or temporal biases. The instrument was validated using an expert panel, and the constructs were later confirmed via PCA and CFA. Although this was done in the context of the studied object of this research (i.e. the Colombian metalworking industry), it is highly likely that the assessment tool could also result valid for other industries, and even other countries since lean goals should remain the same in multiple contexts.

Regarding the studied object, it can be concluded that lean manufacturing practices have gained important recognition in Colombian metalworking industries, regardless of their size and market sector. It is undeniable that companies linked with the automotive supply chain tend to have higher levels of lean implementation, but companies from other sectors are perceiving the benefits of lean and pursuing more structured implementations. In consequence, about half of the companies comprising the sample reported a high to superior level of lean implementation, and that rate goes up to about 75% when accounting also for those with a medium level.

It is also worth noticing that more than half of the companies perceived some kind of improvement on each of the TBL pillars after implementing lean, which is an important result considering that the general sample has a relatively short period of lean implementation. This point to a growing spread of the lean culture among Colombian professionals and manufacturing workers, which can profit from previous experience in other companies to expedite lean implementation in other ones. This also suggest that lean practices have been gradually adapted to the country and industry socio-cultural context rendering more effective in the Colombian metalworking industry. Both conclusions are also supported by the results of the case study presented in Section 3.2.2, where evidence of higher positive impacts were perceived in practices with a higher level of adaptation.

The results of the SEM models confirm that lean indeed plays an important role on the performance improvements on each TBL pillar. However, it is worth highlighting that Colombian companies have started paying more attention to social and environmental outcomes, which should in part justify the efforts to improve in said dimensions. In the context of a developing country (such as this case), companies tend to be highly susceptible to coercive approaches to environmental and social upgrading. This coercion could either come from government legislations that become stricter in response to free trade agreements, or customer demands (especially from developed countries) that put social and environmental standards among their supplier development decision points. Regardless of the case, it is satisfactory to evidence that sustainability is rapidly gaining relevancy among the Colombian industries priorities. There is however a long path to walk still, since, by 2017 (the more recent publicly available), only 3 Colombian metalworking organizations were adhering to the GRI and publishing voluntary sustainability reports.

Therefore, it can be concluded that the Colombian metalworking industry (and Colombian industries in general) are in urgent need of more “hands-on” and empirical research in fields related to modern manufacturing strategies (including lean) and sustainable manufacturing. The lack of communicating paths from industries to universities (and vice versa) can be evidence by the shortage of scientific publications on those fields (at least at well-known journals) that are based on Colombian studies.

An important boost to companies’ sustainable performance, as well as their competitiveness in the current globalized market, could sure come from the integration of the so-called “triple helix”, which includes the government, industries, and academics. If the companies are open to supply certain information and allow some forms responsible “experimentation” (which in the end means being open to prove other ways of doing things), academics will have the resources and data required to conduct research, thus developing and proving new theories that can evolve into practical improvements and innovation for the companies. Finally, the government should provide founding for academics and companies willing to participate in research programs, but also, can take profit of higher revenues resulting from better performing companies. In addition, the results of the research should be used to develop public policies that incentive companies to invest in sustainability and productivity programs with the help of academic institutions, resulting in a virtuous circle of improvement with tangible benefits for the three involved parties.

4.5. Limitations and further paths for research

As with any investigation, there are some limitations worth noticing to the present research. Said limitations however present interesting opportunities for future research that can use the obtained results as a start point to further contribute to the knowledge of both lean manufacturing and sustainability fields. One of said limitations concerns the number of companies in the final survey sample. Although the obtained data sample was large enough to give statistical significance and population generalization capabilities to the results, it was not large enough to conduct tests regarding the influence of many important control variables. In this way, to better understand the complex interrelationships between lean manufacturing and the three TBL pillars, further research will be required in the future, with larger samples, that allow to control for the effects of variables such as company size, time of lean implementation, market sector, or even regional location. The critical success factors for lean implementation and the proposed paths to achieve sustainable performance improvements can become different depending on where the company sits on those control variables.

There have been suggestions in literature that companies related to the automotive industry are more prone to implement lean programs. Said notion was partially supported by the obtained results. Also, there has been debates in literature regarding if big companies are more likely to achieve successful lean implementation than small ones. Large companies have more organizational resources to invest in lean, however, they have more stablished (and usually less flexible) processes that make cultural changes difficult and time consuming, in comparison with small ones (Shah and Ward, 2003). Finally, it has also been suggested that multi-national companies, or companies with a high export to domestic sales ratio, tend to be more committed to sustainability because of increased pressure from their customers and the need to fulfill (in some cases) the regulatory requirements of both the host and the destination nation. Answers to those questions (and others related), could be provided following a similar research setup as the current one, with a larger sample that allow to make inter-group comparison and hypothesis testing with respect to the control variables.

It can be also of interest to consider the mediating effects and interactions of other manufacturing paradigms and trends, such as Industry 4.0, which has been gaining significant interest among practitioners and the academic community, thus creating new knowledge gaps regarding its effect on the studied phenomenon. In the same way, the present research evaluates only internal (i.e. at the manufacturing process level) aspects of LM and sustainable performance, however, from a supply chain management approach, the same models could be tested across different links of the value chain, providing a more comprehensive understanding of how lean practices can extend upstream and downstream from the production process, and how sustainability is likewise affected. This approach could contribute to prove Krause et al. (2009) claim that "*a company is no more sustainable than its supply chain*".

Another limitation of the research is that it was conducted in the context of a developing country. Interestingly, as it was mentioned before in this document, most recent research relating lean manufacturing effects on sustainability has been conducted in developing countries. This could be because of concerns regarding less strict environmental and social regulations on developing economies. However, the environmental threats derived from human activities (particularly industrial operations) and long-term sustainability of manufacturing industries are global level concerns, that should make no discriminations between developed and emerging economies. Therefore, although the results obtained from the present research cannot be completely generalized to companies located in developed countries (constituting a limitation), the developed data gathering instrument can be applied, and the proposed models can be tested, without significant modifications, anywhere in the world. Hence, the test of said models in other countries (developed and emerging) and the comparison of the results, constitute an interesting path for future research, that could help closing the knowledge gaps in the matter and provide foundations for holistic frameworks of sustainable manufacturing that are capable of rendering positive results regardless of the context.

The obtained results, and the derived populational inferences and conclusions, are also limited to the Colombian metalworking industry, where the sample was taken. Although it is possible that many of the results and conclusions can be extended to other kinds of manufacturing industries that deal with similar day-to-day problems and pursue similar performance goals (like plastic or textile and clothing industries), even in other neighbor countries, future research can include the test of the proposed models on said industries and compare the results. Furthermore, the proposed models can be tested in sectors different from manufacturing that are also prone to implement lean, like, the food and pharmaceutical industries, or even, some service industries.

From the methodological point of view, the research is limited because of the use of cross-sectional data. This presents a “picture” of the current state of the studied phenomenon, that is prone to be influenced by transitory contextual factors. When longitudinal data is available, the researcher has the possibility to compare the evolution of the independent and dependent variables and test more meaningful cause-effect relationships. This implies that more research is needed in the future on both proposed models (the trade-offs and the cumulative approach) to evaluate if there is consistency with the obtained results, or as lean manufacturing naturally evolve and Colombian companies acquire a higher level of lean maturity and sustainability awareness, the sustainable performance improvements become more evident and there is no longer evidence of trade-offs. Another worth noticing methodological limitation relates to the indicators employed to measure each one of the constructs for both LM and sustainable performance. Although they were drawn from relevant literature and validated by a panel of experts, it cannot be said that all lean or sustainable performance variables are considered in this research because of the inherent limitations of the SLR (the possibility of some relevant or recent articles being excluded), the subjectivity of the consulted experts, and the context related exclusions, which are however inherent to the *post-positivist* epistemological approach.

Also from a methodological perspective, the present research opens several future paths involving the use of different methodological approaches. The use of action-research (AR) has been gaining significant prominence on both OM and sustainability fields (Antony et al., 2021; Avella and Alfaro, 2014; Egbunike et al., 2018). Action-research aims to perform theory development or testing, while contributing to solve practical problems, with the researcher actively involved on the studied object process (Domingo and Aguado, 2015; Goti et al., 2018). While applying the models of this research under the AR methodological approach it is likely that the much-needed bridges between sustainability theories and their practical application could be developed faster.

Another interesting approach is the use of simulation techniques to mimic the studied phenomenon while overcoming some of the problems related to survey-based researches (Bonilla et al., 2018; Mohamad et al., 2016). Simulation tools and software can provide the means to test multiple scenarios to determine cause-effect relationships between the studied variables (Velásquez Rodríguez and Moreno Mantilla, 2017). In this way the effect of lean practices on sustainability indicators can be assessed on different scenarios, as previously explored by authors such as Diaz-Elsayed et al. (2013), Herrmann et al. (2008), and Solaimani et al. (2021) on different contexts. Simulation results could then be used to create optimization algorithms that can be of practical use for companies while implementing LM and pursuing sustainability goals (Caldera et al., 2017; Sproedt et al., 2015).

The conclusions drawn from the gathered results, allow to think that the cumulative “sand-cone” approach proposed (and empirically validated) can evolve into a more complex and efficient sustainable performance model. The author proposes to call this approach the “virtuous circle” model. In essence, it could be hypothesized that the cumulative performance improvement sequence evidenced in the presence of lean manufacturing, can evolve into a continuous loop of improvement at very high levels of lean implementation (in companies often known as “world class manufacturers”). In this case, lean has a positive effect on operational performance, that in turns improves environmental performance, and finally, social performance (as proved by hypothesis 1 of this research), however, in the “virtuous circle” approach it can be hypothesized that the improvements in social performance would also manifest in a higher level of lean implementation as the employees will be more motivated and committed as a consequence of better work conditions and results, and management will be likely more willing to invest further resources after perceiving tangible returns in all performance dimensions. This will further boost operational performance, reflecting in lower costs, higher quality, less WIP inventories, more flexibility, that in turn should provide more resources to improve environmental performance, and so on. While this closed loop sequence seems to have logic grounds, there are not evidenced suggestions of it in the reviewed literature, making it a novel and interesting future research opportunity.

Finally, it has to be said that as Coronavirus pandemic has been developing worldwide since the beginning of 2020, it is difficult to quantify how it has influenced on the obtained results. Notably, the first cases of COVID-19 were detected in Colombia in March 2020, and by the end of the same month, the entire company was on a complete lockdown that ceased all non-essential activities, including most of the metalworking industry operations. As a large portion of the data gathered through the survey instrument was collected during the partial lockdown that followed after June 2020 (and extended to 2021), it is possible that the priorities of most companies were changed with the health, economic, and social turmoil, and performance improvements perceived, or pursued, prior to the pandemic were no longer relevant or representative to some companies. Furthermore, many companies did not survive the economic repercussions of the lockdown and were forced to close, with the metalworking sector being highly affected as it is largely composed by small companies, and most of them were not related to essential activities (like the food and medical supply chain) that were prioritized at the beginning of the pandemic.

The world economy and manufacturing industries (let alone the Colombian ones) are still recovering from the impacts that the Coronavirus pandemic brought with it. Many repercussions are still manifesting and is likely that new ones will continue to arise for the months (or even years) to come. A sound example is the bullwhip effect that has arisen in global trade and logistic operations. As many countries began re-activation plans for their economies by the end of 2020, the increased demand in goods and raw materials (many of them sourced in Asian countries) overcame the ability of manufacturing companies worldwide to supply it, since many of them were still facing labor shortages and many other restrictions derived from the Coronavirus. There has been reports of a worldwide shipping containers shortage that has delayed international freight and has elevated shipping costs (in some cases more than five times). Many countries have opted to invest in large infrastructure projects to boost employment and help economic recovery.

All the above factors have contributed to a significant increase in steel prices worldwide, among a continuously increasing demand that is not being able to be supplied by the current worldwide production capacity. This phenomenon has negatively impacted the metalworking industries worldwide, with Colombian companies facing scarce raw material availability and costs that continue to increase, even more with the devaluation of the local currency. This has shifted the focus of many companies from long-term sustainability to short-term survival. It will be a long time before a complete understanding of the repercussions of the Coronavirus pandemic is achieved, but for sure, researchers have been gathering important data during these difficult times, and more research will be needed to understand how lean manufacturing and sustainability-oriented manufacturing systems helped companies endure the unforeseen challenges that arose in this turbulent times.

This has opened an important path for research that will become crucial for companies, governments, and humanity at the time of facing worldwide problems that do not discriminate geographical borders in this globalized world. The manufacturing industry will continue to play a major role in the globalized environment of the future, and it is of outmost important that the “triple helix” integrating researchers, companies, and government, continue working towards the development of frameworks that ensure its sustainability in the light of the unpredictable challenges that will continue to arise in the years to come. Knowledge and scientific developments derived from continuous research on these topics will have an essential role in ensuring outcomes that help to close the high economic develop gaps present worldwide, without creating irreversible impacts on the environment and, ultimately, contributing to human life quality development on universal standards.

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APPENDIX A: SURVEY VALIDATION INSTRUMENT

APPENDIX B: INVITATION LETTER TO EXPERTS AND VALIDATION INSTRUCTIONS

APPENDIX C: FINAL DATA COLLECTION INSTRUMENT

APPENDIX D: INVITATION LETTER TO CASE STUDY

APPENDIX E: SELECTED COMPANIES COMPLETE DATABASE

APPENDIX F: INVITATION LETTER TO FINAL SURVEY

APPENDIX G: COMPLETE SURVEY RESULTS