DOI: 0

Silva, M. H. B., Muianga, E. A. D., Oliveira, K. P. R. & Granja, A. D. (2024). Insertion of modular construction aligned with lean principles: a conceptual map model. In: D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 831–844). doi.org/10.24928/2024/0136

INSERTION OF MODULAR CONSTRUCTION ALIGNED WITH LEAN PRINCIPLES: A CONCEPTUAL MAP MODEL

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ABSTRACT

The construction industry presents increasing levels of competitiveness among sectors, increasingly demanding products with higher value-added and sustainability. However, problems such as: production capacity, product quality, meeting deadlines, cost control and low productivity are always in evidence for this industry. Therefore, this work aims to present strategies for inserting modular construction in projects in the housing sector. This constructive method allows the application of innovations, increased productivity, control of costs and deadlines, products with greater added value, as well as the development of lean principles in the sector. Due to the complexity involved in the theme and the limited academic development and market for the application of this construction method, this work presents a conceptual map with strategies for inserting modular construction, offering a synthetic vision for companies in the sector that wish to follow the path of modular construction can better understand the main opportunities, barriers, risks and strategies. Market externalities and alignment with lean principles are also presented. For this purpose, the Design Science Research methodological approach was used.

KEYWORDS

Conceptual Map Model, Modular Construction, Lean Construction, Real Estate.

INTRODUCTION

The construction sector is important throughout the world economy. Due to the high competition, project-oriented industries such as the construction industry need to introduce more efficient systems (Toosi & Chamikarpour, 2021). The sector coexists with the design of complex products and has some peculiar characteristics, inherent to its environment (Koskela, 1992).

Efforts to promote innovation and modernization into the construction sector are in development, however, less than other sectors, classified as a low-technology sector in research, development, or innovation practices application (Reichstein et al., 2005). It is perceived as a sector constantly at risk, given the reduced profit margins, high production costs and little

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concern for the end customer, also considering its slowness in adopting new knowledge (Seaden & Manseau, 2001). The lack of knowledge induces the use of conventional materials, products or services, inhibiting the use of innovative construction technologies.

In scenarios where real estate heats up and increases in input and labor costs, construction companies are forced to look for alternatives to conventional construction systems. In this sense, the use of off-site construction elements can be considered a path (McKinsey and Company, 2020).

Modular construction (MC) has shown superior results in terms of efficiency, when compared to the results of traditional construction. However, MC presents barriers that should be considered and overtaken, such as knowledge gaps regarding the high initial cost, the requirement for an innovative design process, the complexity of the supply chain and social perception (Broadhead et al., 2023).

Another fact that should not be unconsidered when thinking about the transition of traditional construction systems to MC is the growing need to produce housing units around the world. The world population grows at a rate of approximately 200K inhabitants per day in large urban centers (WEF, 2016). This growth imposes the need to provide adequate housing infrastructure. Considering the issue of productivity and conventional technologies, it is unlikely that the production of housing units will be able to meet this growing need for new buildings.

MC can help reduce the housing deficit, given the characteristics of such a constructive mode. Providing off-site prefabricated components with precision, efficiency, controlled cost, quality, safety and functionality increases the overall productivity of architecture, engineering and construction (AEC) industry. Countries such as the United States, United Kingdom, Sweden, Australia and China have been adopting modular construction to solve the housing deficit (Bello et al., 2023).

The use of industrialized construction methods may help solve important and historical construction problems, such as workflow instability, low productivity, lack of punctuality and delays (Deakin et al., 2020). These problems are also solved by applying lean practices. The benefits of applying lean concepts in MC have been documented in various case studies (Velarde et al., 2009; Nahmens and Mullens, 2012; Yu et al., 2013; Heravi and Firoozi, 2017). The main benefits are increased productivity; reduced waste, especially costs; improved safety conditions; increased job satisfaction and improved sustainable solutions.

The MC industry has an affinity with the manufacturing industry. This increases the synergy between lean concepts and MC, without forgetting the challenges that MC brings, such as the need for product customization, variable market demand and the involvement of the supply chain (Höök and Stehn, 2008). Thus, lean practices can be incorporated into the entire production flow of MC, involving the application of lean design management, lean supply chain management, lean production management, lean transportation management and lean site-assembly management (Innella et al., 2019).

The main questions of this work are: What is the contribution of MC in the construction sector?; What are the main barriers, opportunities and risks for expanding the use of MC in line with lean principles and how to consider them in viability studies?

The path to be taken by companies in the civil construction sector, which seek to align and implement modern and sustainable construction methods (such as MC) still has numerous barriers and doubts. Therefore, this work aims to present the beginning of a solution to this problem, with the aim of facilitating, through a conceptual map, the choice of the best path for the insertion of MC.

MODULAR CONSTRUCTION

DEFINING THE CONCEPTS AND PURPOSES

MC is a different way from the traditional building system and can be defined as an industrialized construction system compatible to be transported between the factory and the construction site (De Carvalho & Scheer, 2019). In this construction mode, work at the final construction site is minimized and prefabrication is maximized. Technologies are employed that facilitate off-site manufacturing and the transport to the assembled site, like a Lego® (BCA, 2022).

The term used for MC may suffer considerable variations. The definition is different in distinct parts of the world, as it considers different views and interpretations, more or less complete. The following terms are found in the literature: prefabrication, pre-assembly, modular construction or off-site construction, which can make understanding difficult (Gosling et al. 2016). Other terms may still exist: prefinished volumetric construction, permanent modular construction, prefabricated modular construction (Doermann et al., 2020). These terms are used interchangeably and encompass a variety of different approaches and systems (Bertram et al., 2019).

Industrialized construction is the rationalization of the work process in the construction industry to achieve cost efficiency, greater productivity and quality (Girmscheid and Scheublin, 2010). Off-site construction is the planning, design, manufacture and assembly of construction elements in environments outside the construction site (Australia, 2022). In this work, the definition adopted is that modular construction is the process in which a building is constructed off-site, under factory plant conditions with a controlled environment, using materials, codes and standards that resemble conventionally built facilities (MBI, 2019).

In addition to the definition of MC, this can be considered as the pinnacle of prefabrication, involving the most integrative measures of modules made in a factory with greater added value (Pan & Hon, 2020). It refers to the manufacturing and assembly of modules in a location other than the final installation location, after which such modules are sent to the installation location and assembled to form a complete building (Doermann et al. 2020). In general terms, modular construction involves the production of standardized components of a structure in an off-site factory, for subsequent assembly at the final construction site (Bertram et al., 2019).

STRATEGIES TO MODULAR CONSTRUCTION

Modularization, prefabrication of subsystems, standardization and industrialization of processes, increasing product value and making processes more efficient in terms of resources and time (Jonsson & Rudberg, 2013). Strategies to modularization of construction have recently attracted interest from academics and professionals in the sector. However, there are few studies that comprehensively classify different strategies. These must be suitable to develop innovative design solutions, improve the quality, cost, schedule performance of a project, allow flexibility in the use and maintenance of a building (Peltokorpi et al. 2017).

Modular product design is at the heart of any effort to utilize modularization in the production system. A "modular" design differs from the conventional strategy in that it includes a discrete mapping of functional elements to product components and specifies interfaces between them (Ulrich, 1995). Modularity becomes an attribute of the product (activity of structuring a product into modules). Coupling between modules allows product variants to be created, mixing and matching components according to the functions each user needs (Bask et al. 2011). Functions are hierarchical and that a single component must implement a specific "package of functions" rather than a single specific function (Peltokorpi et al. 2017).

To the production strategy, decisions regarding the necessary equipment are required, as well the factory layout, the level of automation required, production organization and planning methods (Ravn et al., 2015). Therefore, attention must be paid to this issue from the beginning of the project, considering the competitive priorities defined for investment in the enterprise (Jonsson & Rudberg, 2013).

Peltokorpi et al. (2017) presents four paths to modularization, according to the degree of product standardization and off-site production, with traditionally constructed buildings at the lower end evolving to the upper end with fully modular buildings. The paths are: – a. modular buildings (3D - pre-assembled volumetric units, composed of whole or connected modules, meaning the highest degree of off-site production and standardization); b. volumetric pre-assembly (building modules are produced off-site and assembled at the final construction site inside an independent built structure – example – the insertion of a bathroom or a kitchen; c. non-volumetric pre-assembly (2D - pre-assembled elements that do not create usable space – example – wall panels, floors or roofs); d. conventional buildings (raw materials and components, such as bricks and mortar, are used in construction at the final building site, indicating a high degree of customization and a lower degree off-site production and standardization).

The set of the first three categories provides a good basis for investigating modularization strategies, since the distinction between them is based on the hierarchical "packaging" of functions embedded in a single component. Understanding the different dimensions of MC, their interconnections and possibilities for achieving various objectives may support professionals select the most appropriate strategies for a specific context (Peltokorpi et al. 2017). Such strategies, for this work, are defined in three: construction with panels (2D), volumetric (3D) and hybrid (2D + 3D).

OPPORTUNITIES AND BARRIERS TO MODULAR CONSTRUCTION

In general literature on this topic, similar impressions from different authors, from different schools and parts of the world are found (BCA, 2022; Bello et al., 2023; Bertram et al., 2019; Broadhead et al., 2023; Deakin et al., 2020; Doermann et al. 2020; McKinsey and Company, 2020; Pan & Hon, 2020). In one hand, the main opportunities for MC: accelerated construction cycle, increased productivity, increased quality, safer and healthier working conditions, enables cost control, reduced volumes of construction components to be stored, improved sustainability (reduced waste of materials, the generation of dust, noise and carbon emissions, water consumption, as well as the possibility of greater recycling or relocation of such modular buildings). In other hand, the main barrier are: high initial costs for production and training, more complex of transport and logistics, production capacity limitations, market vulnerability, lack of technical knowledge, adversarial/resistant culture of potential customers, inadequate business model and supply chain configuration, lack of specific standards, codes and regulations, government support, lack of qualified professionals.

LEAN PRINCIPLES IN MODULAR CONSTRUCTION

Lean principles have greatly evolved through the Toyota Production System (TPS). When developing their products, companies must seek greater competitive advantage, launching better products onto the market more quickly, with attractive prices for their potential buyers and eliminating waste in production.

Since the origins of this new production paradigm, several sectors have made efforts to apply it. The pioneering work to introduce these principles in civil construction was Koskela (1992). Since then, researchers and companies have sought to interpret and adapt to this environment, as well as discussions and case studies can be found in the International Group for Lean Construction papers (Picchi, 2003).

However, lean principles became known worldwide through the publication of Womack et al. (1990), where briefly, the objective is to produce more value for the customer with less waste. Some of the lean tools are present in the AEC industry, like: Last Planner System (LPS), Value Stream Mapping (MFV), Integrated Project Delivery (IPD) and 5S. The benefits linked to their application are improved quality, reduced waste, increased productivity, increased safety and health at work (Almeida & Picchi, 2018).

Considering the five lean principles proposed by Womack & Jones (1997), disseminated and adopted in several industrial sectors, this work seeks to present their alignment with strategies for insertion of MC – a. Value: understand what value is for the customer and offer greater added value; b. Value Stream: identify and eliminate waste throughout the value chain; c. Flow: production in stable flow, without interruptions; d. Pull: produce only when demanded by the customer or previous process; e. Perfection: continuous improvement through rapid detection and resolution of problems at the base. Lean principles aim to continually improve the competitiveness of companies in the sector, employing methods that seek to reduce waste and meet customer requirements. Issues involving sustainability are important lean guides (Koskela et al., 2010). Through methods and tools, we seek to mitigate common problems in the sector, such as the high environmental impact and lack of efficiency in production (Almeida & Picchi, 2018).

Some of the main impacts and benefits arising from the implementation of lean principles may be collected in publications: standardization of work, improvement in productivity and working conditions, focus on value, formation of specialized teams, improvement in planning and control of work, transfer of knowledge between projects, collaborative project, integration with suppliers, reduction of lead time, reduction of waste and costs, greater customer satisfaction, increased company competitiveness (De Freitas & Costa, 2017).

The existing literature about modular construction addresses dispersed points of view. It is common for MC to be approached with individual factors such as design, planning, coordination, automation or benefits and barriers. At the same time, the literature about the synergy between lean principles and MC is also dispersed. Each work usually evaluates the specific use of a concept or tool. So, there is a gap in the understanding of the alignment of these concepts in a systematic way. Thus, the main constructs of MC are dispersed, especially when related to lean principles. For this reason, this work uses concept maps to define and relate the main constructs of the subject. This creates a logical sequence between the constructs to guide the adoption of MC by organizations.

RESEARCH METHOD

Design Science Research (DSR) was applied as a research methodology. DSR is a method which seeks to solve a specific problem, develop innovations, methods, models, product and process improvements (Dresch et al., 2015).

The objective of DSR is to develop concepts for solving complex and relevant problems in a given context, often based on a multidisciplinary study. DSR combines description and prescription (Aken & Joan, 2004). This approach is seen as a way of producing scientific knowledge that aims to lead to innovative solutions and artifacts to solve real problems and, at the same time, contribute to the evolution of theory in the area in which it is applied (Cole et al., 2005).

The literature provides guidelines for the DSR process (Shrestha et al., 2018). DSR presents six phases summarized from: development of a relevant practical problem; definition of objectives and expected results; development of a artifact (models, methods, constructs, instantiations, and design theories); demonstration of artifact effectiveness; evaluation; and diffusion (Dresch et al., 2015).

This research is part of a doctoral research, in which it is expected to formulate a complete model for the insertion of MC in the sector. Thus, the research we sought to understand the alignment of the MC concept and its contribution to the construction sector. For this, a literature review was developed to understand and identify MC strategies, and opportunities for its application. Studies on MC were assembled and data were collected to construct the conceptual map model.

ARTIFACT - CONCEPTUAL MAP MODEL

The development and use of a new theory may present some challenges to ordinary understanding. Conceptual maps, among many other tools, may be used to clarify the understanding of a new theory. Such maps present a visual structure that can graphically explain what is being studied (Maxwell, 2012).

Concept maps can be created for a variety of purposes, such as: making information from existing theories visible, clarifying an existing theory (allowing implications and limitations to be observed), developing a theory (helping to observe connections) and identifying gaps or contradictions, helping to find better solutions for a particular theory (Maxwell, 2012).Concept mapping has been shown to help learn, create new knowledge, structure and better manage organizations (Novak & Cañas, 2008).

Although concept maps may seem like just a graphical representation of information, understanding this tool and using it properly will lead the user to see that this is a powerful tool. The organization of concepts with connecting words can be simple at the same time, but also full of complexity and important meanings. A conceptual mapping was developed in this research to understand the concept of MC and its association.

MODULAR CONSTRUCTION CONCEPTUAL MAP MODEL

The Conceptual map model (Figure 1) presented the main characteristics, limitations and points of attention for each of the strategies considered, as well as seeking to relate the main barriers, opportunities, risks and externalities that surround MC. The tool (Figure 1) is composed of two parts: the first, which involves the concepts contained in boxes, and the second, which involves the relationships between these theoretical concepts. Furthermore, it also presents connectors, words that connect concepts and express relationships between them (Novak & Cañas, 2008). In line with each of these aspects, connections with lean principles were also presented.

As a way to guide the good understanding and application of the conceptual map model, a brief explanation of its use and the main themes involved is interesting. The MC is organized through six strategies: opportunities, risks, externalities, 2D MC, 3D MC, hybrid MC, which are associated with lean principles. For each strategy, information gathered in literature to construct the conceptual map are presented, as follows.

OPPORTUNITIES

Control
Safer
Quality
Sustainability

Initially, the opportunities of MC are verified, such as control and reduction of construction deadlines, cost control, healthier and safer working conditions, better control of quality standards and the possibility of developing a more sustainable environment. The deadline to execute these works is shorter than those for conventional works, and significant reductions can be achieved (McKinsey and Company, 2020). Cost control comes with the possibility of increasing productivity, due to better defined construction standards. This connects with the lean principle of standardization of work applied to construction and can increase performance with the use of lean cost management, the Target Value Design (TVD) (Koskela, 1992; Ballard, 2011). Regarding working conditions, there is less physical workload and fewer workers at the final construction site, improving the general organization and increasing work safety (Deakin et al., 2020). Lean practices address the concept of safety in its essence, bringing it from the theory of the Toyota Production System to lean construction (Koskela, 1992). Sustainability is also improved, being perhaps one of the greatest benefits of opting for MC, with the reduction in consumption of energy sources and natural resources, carbon emissions, waste generation, and general impacts on communities around to constructions (Bertram et al., 2019). The use of lean principles improves the sustainability of products, especially with the use of Value Stream Mapping (VSM) (Rosenbaum et al. 2013).

RISKS

Construction Standards

Business model

Suppliers

There are additional risks mapped, collected through the authors' work experience in construction and literature. To insert MC, it is necessary to develop specific standards, codes and regulations for this type of construction (Bello et al., 2023), without which, linked to incentives from government entities, the dissemination and encouragement of industrialized construction cannot be advanced. There is also a need for a new business model for companies in the sector and the adoption of a collaborative project, including the required digital transformation and improvement of relationships with suppliers. This can be achieved through the effective use of the value stream principle, using the VSM, for example.

EXTERNALITIES

Traditional methods

High competition

Resistant culture

Value understanding

Resource

Delimitation

Previous studies (Deakin et al., 2020; Bello et al., 2023; Doermann et al., 2020) have demonstrated that the main externalities and challenges focus on issues involving market conditions and the culture of potential customers to the MC. This collaborates with the first lean principle, which deals with value. It is necessary to evaluate the value chain, especially considering customer requirements (Womack & Jones, 1997). The high competition between companies in the sector and the preference of agents in the production chain for traditional methods, has an arrow indicating the box that the decision by MC, since these are aspects that must be considered in the decision. Searching for improvements in the production system and breaking away from the use of traditional methods is related to the lean principle of perfection, which involves the search for continuous improvement (Womack & Jones, 1997). Regarding the opposing culture and understanding the value propositions of potential customers, it was decided to indicate the opposite direction for the indicative arrows, since they are basic and conditioning aspects and must be analyzed even before any intention to the construction method. Finally, we have the challenges related to financial resources for production - which are considerably higher, since it is assumed the need to install and maintain production in an off-site manufacturing environment (Deakin et al., 2020) and price delimitation that keeps the product competitive compared to the market in general (De Mello et al, 2015). For these last two, a two-way relationship was used, as it is understood that they are necessary for the decision of the MC insertion, as well as being feedback with information within the process. Thus, the use of lean concepts and principles can reduce these challenges by eliminating waste and optimizing resources, as has been widely presented in lean literature.

2D MC

Design process
Workforce
Needs
Capacity
Flexibility
Entry, Cost

When evaluating the 2D strategy, a simpler modular construction method, it appears that it is quite attractive as a gateway to this world. Transport costs are lower, since the panels are two-dimensional, allowing a greater number of elements in loads. Like all labor involved in MC, it requires workers with greater training compared to traditional construction. It is important to highlight the production capacity of panel suppliers, a large quantity of flat elements are required.

3D MC

Impacts
Resources
Productivity
Construction speed
Specialized labor
Flexibility

As MC strategies are considered, when evaluating the 3D strategy, a greater number of considerations are made. This construction mode, even today, is disruptive, with almost all construction being off-site. Issues relating to logistics and transport stand out, given the size of the volumetric modules, transport conditions and costs, as well as the need for large equipment for lifting and coupling the modules. In this scenario, there is a greater need for initial resources in the manufacturing units to enable the construction of modules (Bello et al., 2023), on the other hand, there is difficulty in obtaining resources from financial institutions, both to finance production and to finance potential buyers of the units, who have a much shorter period of time to amortize payment for the product during the construction phase (which in many cases is a fraction of the time compared to traditional construction). There is also low architectural flexibility and great difficulty in changing the project on site, which requires more sophisticated and integrated projects, in addition to more specialized labor.

HYBRID MC

Flexibility
Vulnerability
Optimisation
Workforce, Areas, MC use
Impacts

As for the hybrid strategy (2D+3D), at the current stage of MC knowledge and application, it can be considered the most ideal scenario. Combining flat and volumetric elements optimizes transport and logistics, as well as allowing wider use of off-site elements. These factors lead to medium architectural flexibility, allowing greater customization of buildings.

The lean principles are indicated in the conceptual map model, linked to the constructs, in order to indicate the principle evaluated as most adherent and aligned. What can be seen is that most of the alignment of lean concepts are related to “value”, where one must seek to understand what value is for the customer and offer greater added value through the chosen strategy. This is in line with customer resistance, one of the main barriers to adopting modular construction. By analyzing, managing and delivering value, the customer reduces their resistance. Reducing customer resistance can increase the procurement of modular products, bringing a gain in scale. Increased scale helps to reduce other barriers, such as direct and indirect costs and financing. For some constructs, lean principles were not aligned, due to the difficulty of establishing the most appropriate principle or because this establishment was not possible.

The main contributions of this research were the following: (i) Classification of the MC concepts into strategies groups and associations between them; (ii) Proposal with opportunities of MC context with inclusion of different models (iii) Results of the organization and relationships between the constructs, within of a group of strategy. The conceptual map classifies and organizes the main constructs of MC and evaluates their relationships with each other. The map includes the relationship of the constructs with lean principles and presents the externalities that impact the main constructs.

With the conceptual map, the Architecture, Engineering & Construction sector may identify possible paths for adopting MC, evaluating different modularization strategies based on their needs, conditions and points of attention. With the externalities, organizations can structure strategies to overcome the challenges pointed out. The MC may contribute to MC adoption perspectives, considering externalities (barriers) and main opportunities in each strategy.

Overall, the conceptual map provides a basis and direction for decision-makers to choose paths for adopting MC, taking into account the requirements and resources needed for each path. This leads to a more conscientious and informed adoption, with well-defined paths.

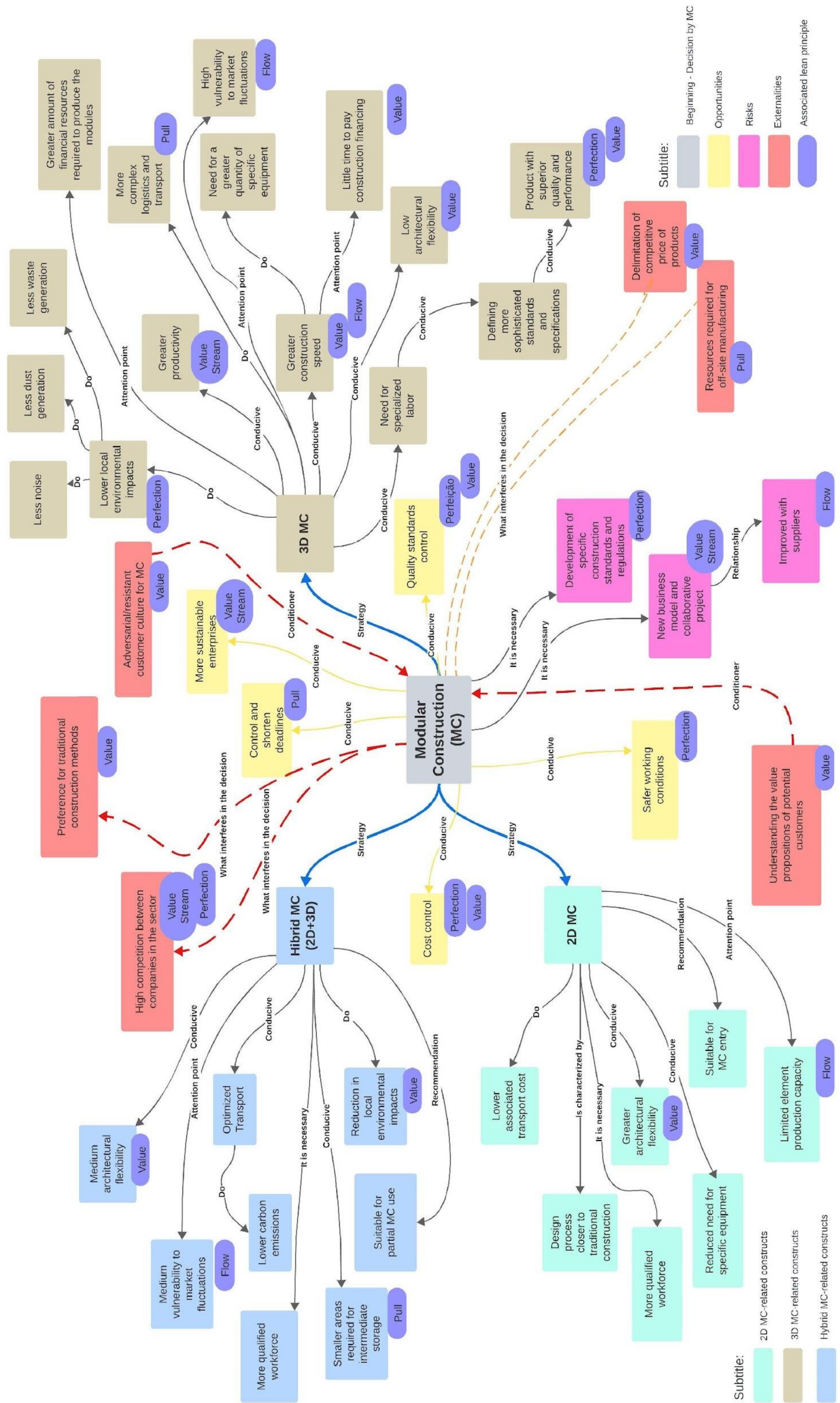

Figure 1: MC Conceptual map model. Source: The Authors.

CONCLUSIONS

Lean principles allow complete alignment with MC, since it is a mentality already widely spread in the manufacturing industry, as well as bringing new paradigms, applicable to the business, involving the development of the product as a whole and the relationship between agents of the production chain.

Precisely because MC requires that construction companies, markets and potential clients have new conceptions about this construction method, the application and alignment of lean principles allow choosing the best paths to be followed for the insertion and expansion of employment of this constructive way, considering the necessary reviews of project flows, supplies and execution of works, as well as the production and business model of each company in the sector.

The conceptual map model presented facilitates the understanding of possibilities and paths through the synthetic visualization of alternatives. Each one of the constructs presented can be analyzed in more detail, allowing one to choose the most appropriate MC strategy for each company or enterprise.

The lack of studies that analyze the MC application through different strategies, in different contexts, mainly where traditional construction models are more effective limit the analysis of MC applicability in a real context. Thus, future and complementary work may explore each MC strategy, adapting and analyzing the particular ones in light of the main opportunities and barriers identified. As for lean principles, specific works may study each alignment proposed for each construct present in the conceptual map model. Increased studies in this area will certainly lead to the development of more innovative, sustainable construction techniques with greater added value.

ACKNOWLEDGMENTS

The authors would like to thank the academics who participated in this study, providing important insights to construct the conceptual map model. The research was funded by CNPq [421370/2023-8; 314760/2023-7]. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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