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Miguel Pereira Stehling

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Campinas, 08 de agosto de 2019

DEDICATION

I dedicate this work to the honor of
every member of my family who
prayed for me citing the name of my
father, Miguel Stehling, and to the
memory of my mother,
Ephigenia Pereira Stehling

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The starting point for the research effort describeb in this dissertation was my experience in designing and manufacturing woodworking building components in the Architecture Engineering and Construction Industry. Twelve years dealing with the design and fabrication problems of fabricators and subcontractors of custom products, aroused my interest to find a solution to practical problems faced by fabricators of engineered-to-order components.

First, I want to thank GOD for guiding my steps throughout the journey of my life, as a loving Father and close Friend. I thank my supervisor, Professor Regina Coeli Ruschel, a highly qualified scientist, who directed my research wisely, supported me, encouraged me, became friends, and marked deeply my professional and academic life. I want to thank the examiners, Professor Ana Lúcia Nogueira de Camargo Harris, from Universidade Estadual de Campinas, Professor Patrícia Stella Pucharelli Fontanini, from Universidade Estadual de Campinas, Professor Márcio Minto Fabrício from Universidade de São Paulo, Professor Frederico Braida Rodrigues de Paula from Universidade Federal de Juiz de Fora, and Professor Neander Furtado Silva, from Universidade de Brasilia, for their valuable suggestions for improvement of this thesis. I thank all the employees of the Universidade Estadual de Campinas citing the name of Eduardo Estevam da Silva who represented the willingness to always assist in the fulfillment of the commitments with the University. To all the Brazilian people who with their taxes contributed to my academic formation, I want to express my desire to repay back with my work. Lastly but not least, I thank my beloved wife Amelia Meireles Stehling, who accompanied me closely in this great challenge, celebrating, crying, praying and strengthening me. Camila and Karine, wonderful daughters, I love you!

ABSTRACT

An increasing number of fabricators has pursued Mass Customization (MC). MC is a system that uses information technology, flexible processes, and organizational structures suitable to provide individually designed products at a cost near that of Mass Production. The higher the customization level, the more significant the benefits, but also the operational costs. Therefore, the objective of this research was to evaluate the benefits of Building Information Modeling (BIM) for achieving a higher level of MC. The research focused on the formulation of a solution that enables reconfiguration of fabricators structures and processes into BIM mediated mass-customized production system. This study was carried out through a Design Science Research and the results are: (1) a description of the engineered-to-order manufacturing process of a small fabricator of kitchen cabinetry; (2) an investigation of the existing knowledge related to the impact of BIM in the context of MC; and (3) the design, development, and evaluation of a model and a method for BIM adoption integrated to MC strategy for small fabricators of kitchen cabinetry. A hierarchical model to incorporate BIM into automated engineered-to-order building component was proposed with complex and interdependent relationships among the constructs of Custom-driven Design, MC Adoption Strategy, BIM integrated to Fabrication and Digital Fabrication in MC. The model promotes the production to become part of the design and vice-versa. The proposed method to implement and apply the model considers the following steps: web-based elicitation, customized schematic design, customized production design, customized fabrication, and customized assembly. In the proposed method, the client plays an active role in the process, through personal meetings or interacting with a Web database application. The method encompasses the use of patterns, the application of visual and object-oriented programming concepts in BIM libraries, and, design semantics embedded both into a web database application and into the software that the CNC machine manufacturer provides. The observed impacts were on processes, skills, and fabrication. In terms of processes, the impacts were on modeling, information sharing, precision, and collaboration. In terms of skill, the impact was the need for new competencies among designers. In terms of fabrication, the impact was on production and automation. Parametric modeling allows the development of complex BIM components. The elicitation through web application provides the accuracy and reliability of data. The concept of small production cells acting inside the company enhances collaboration. The contribution of this research is the detailing of the complete process of incorporation of BIM to the design and manufacturing of Engineered-To-Order building components.

Keywords: Mass Customization. BIM. Web Database Application. Design and Fabrication of Customized Furniture.

RESUMO

Um número crescente de fabricantes tem buscado a Customização em Massa (CM). CM é uma estratégia de produção que utiliza Tecnologia da Informação, processos flexíveis e estruturas organizacionais adequadas para fornecer produtos específicos a um custo próximo ao da produção em massa. Quanto maior o nível de customização, maiores os benefícios, mas também os custos operacionais. Portanto, o objetivo desta pesquisa é avaliar os benefícios da Modelagem da Informação da Construção (BIM) para se obter um elevado nível de CM. O foco da pesquisa foi na formulação de uma solução que permita reconfigurar estruturas e processos de fabricação em CM mediados por BIM. O estudo foi desenvolvido através de uma *Design Science Research* e os resultados são: (1) uma descrição do processo de fabricação sob encomenda de um pequeno fabricante de armários de cozinha; (2) uma investigação do conhecimento existente relacionado ao impacto do BIM no contexto de CM; e, (3) o projeto, desenvolvimento e avaliação de um modelo e um método para adoção do BIM integrado à estratégia de CM para pequenos fabricantes de armários de cozinha. Um modelo hierárquico para incorporar BIM em componentes de edifícios projetados sob encomenda foi proposto com relacionamentos complexos e interdependentes entre os constructos: Projeto personalizado, Estratégias de adoção de CM, BIM integrado à fabricação, e Fabricação digital em CM. O modelo promove a produção a se tornar parte do projeto e vice-versa. O método proposto para se implementar e aplicar o modelo considera as seguintes etapas: elicitação baseada na Web, projeto esquemático customizado, projeto de fabricação personalizado, fabricação personalizada e montagem personalizada. No método proposto, o cliente desempenha um papel ativo no processo, por meio de reuniões pessoais ou interagindo com um aplicativo de banco de dados da Web. O método abrange o uso de padrões, a aplicação dos conceitos de programação visual e programação orientada a objetos em bibliotecas BIM, e a semântica do projeto incorporada tanto em um aplicativo de banco de dados da Web quanto no software fornecido pelo fabricante da máquina CNC. Os impactos observados foram sobre processos, habilidades e fabricação. Em termos de processos, os impactos foram sobre a modelagem, o compartilhamento de informações, precisão e colaboração. Em termos de habilidade, o impacto foi a necessidade de novas competências entre os projetistas. Em termos de fabricação, o impacto foi na produção e automação. A modelagem paramétrica permite o desenvolvimento de componets BIM complexos. A elicitação através de aplicativos da Web fornece precisão e confiabilidade aos dados. O conceito de Pequenas células de produção atuando dentro da empresa aprimora a colaboração. A contribuição desta pesquisa é o detalhamento de todo o processo de incorporação do BIM ao projeto e fabricação de componentes da edificação projetados sob encomenda.

Palavras-chave: Customização em Massa. BIM. Web Database. Projeto e Fabricação.

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ABBREVIATIONS

AEC -	Architecture, Engineering and Construction
ASCE	American Society of Civil Engineers
CEO	Chief Executive Officer
CNC	Computer Numerically Controllers
DBMS	Database Management System
BDTD	Biblioteca Digital Brasileira de Teses e Dissertações
ETO	Engineered-To-Order
HTML	HyperText Markup Language
HVAC	Heat, Ventilation and Air Conditioning
IFC	Industry Foundation Classes
MC	Mass Customization
MTO	Made-to-order
MTS	Made-to-stock
PHP	Hypertext Preprocessor
RDBMS	Relational Database Management System
SLR	Systematic Literature Review
SME	Small and Medium Enterprise

SUMMARY

1. INTRODUCTION

Several building components are one-of-a-kind products, and, one-of-a-kind products are manufactured mostly under the engineered-to-order strategy. The production of engineered-to-order components with the efficiency, low-cost and high volume of the mass production is a concept named Mass Customization (MC). According to Khalili-Araghi and Kolarevic (2016), Mass Customization in the AEC industry is a relatively new concept. They say that Mass Customization is a complex system that still carries some challenges, and a new method of customer participation in the customization process must be developed.

Some of the Mass Customization challenges pointed out by Khalili-Araghi and Kolarevic (2016) are matching customer preferences with product specification, technical issues related to the system interface and personnel skills to perform design tasks in the MC context. They point out that building customization should not be limited to geometry customization, but efforts should be made to integrate geometry with appliances, materials and other variables. Finally, they say that dimensional customization and design validation could be examined through interactive website platforms.

Farr, Piroozfar, and Robinson (2014) investigated how BIM can facilitate the Mass Customization process in the AEC industry. They say that Mass Customization is a manufacturing strategy that adds value to the AEC industry, but it has not been fully implemented in this sector, partly due to the fragmented nature of the supply chain, but also because of the incapability of the Information and Communications Technology (ICT) infrastructure to provide a dynamic interaction mechanism amongst stakeholders. They say that BIM applications can potentially provide the ICT required for MC and concluded that researches need to address interfaces with XML/HTML files and SQL databases to create a web-based application with an easy to use, and user-friendly Graphical User Interface. According to Luth (2011), the current IFC schema has served the purpose of interoperability, but it is “bogged down” with representations of database objects. What is needed is a simplified schema for the database containing form, function, and behavior of the building systems. In the very words of Luth, *“if the database follows a universal standard for schema and content, there is no need for interoperability – everyone* *operates on the same database”*. Luth adds that a building information model should be independent of the individual software packages and graphical interfaces.

The problem approached in this research arised from the interest to find a solution to practical problems faced by engineered-to-order fabricators. Some of the practical problems that fabricators and subcontractors of custom products have with their existing processes are:

- The low productivity in the design detailing the process for Digital Manufacturing in the Mass Customization context at the woodworking industry.
- Lack of knowledge of BIM impact in Digital Manufacturing in the context of Mass Customization.
- Lack of knowledge in implementing BIM in small businesses, more specifically in design and manufacturing of engineered-to-order products.
- Lack of integration among sales, marketing, basic conceptual design, detailing engineering design and production.

1.1. Objectives

Therefore, the general objective was to propose how to incorporate BIM into automated engineered-to-order building component.

As specific objectives were highlighted the following goals for the development of the research:

- Describe the design, engineering and production processes of engineered-to-order components, through a case study in a small custom kitchen manufacturer.
- Through a systematic literature review, investigate the existing knowledge and artifacts related to the impact of BIM in the context of Mass Customization;
- Through an action research,[1] design, develop and evaluate artifacts for BIM adoption integrated to MC strategy for subcontractors and fabricators of custom kitchens and other furniture cabinetry.

[1] Action Research is a systematic way of reflective thought, discussion, decision and action about what goes on in a specified environment and how to get data from it and develop interventions that will help to improve that environment. Gil (2010) defines action research as a type of empirical based research conceived and carried out in close relation with an action aiming to solve a colective problem.

Considering the research problem identified and the proposed objectives, the main hypothesis of this research is that fabricators of engineered-to-order components can achieve Mass Customization with the mediation of BIM and Web database applications.

1.2. General Organization of this work

The following composition of chapters is adopted in this text.

Chapter 1 presents an introduction with the problem identification, the general objective of the research and three specific objectives. **Chapter 2** encompasses the conceptual background that substantiates the research. The thematic of engineered-to-order components fabrication and Mass Customization are presented in the context of five manufacturing strategies that range from pure standardization to pure customization. BIM benefits, system requirements and adopting strategies for subcontractors and fabricators of engineered-to-order components are presented. In order to give theoretical support for the research's proposed artifacts, the thematic of digital fabrication and web database applications are also presented. **Chapter 3** summarises the research method adopted which is the *Design Science Research.* It encompasses other methods, as the awareness of the problem stage is conducted through a case study and the artifact's proposition, design, development, and evaluation are conducted through action research. **Chapter 4** summarizes the problem awareness performed through a case study within a subcontractor that fabricates engineered-to-order components for kitchens and other cabinetry. **Chapter 5** presents artifacts identified by a Systematic Literature Review. **Chapter 6** presents the artifacts proposed to solve the research problems. **Chapter 7** presents the artifact's design, development, and evaluation performed through an Action Research in an Engineered-to-Order designer and fabricator of kitchens and other furniture cabinetry. **Chapter 8** presents the formalization of the learning achieved during the research process. **Chapter 9** brings the results of the research with the main decisions made as well as the limitations of the research. This chapter brings also an account of the research's contribution to scientific knowledge.

Finally, the appendices from A to J demonstrate the documentation produced during the development of the research. **Appendix A** shows the selected primary studies according to criteria defined in the Systematic Literature Review.

Appendices from B to F show the forms for conducting the systematic literature review in each search source, respectively named, Emerald insight, Scopus, Web of Science, American Society of Civil Engineers – ASCE, and Biblioteca Digital Brasileira de Teses e Dissertações - BDTD Finally, **Appendix G** shows all the research centers involved with the artifacts identified. **Appendix H** shows the organization of data from the Systematic Literature Review in order to identify classes of problems. **Appendix I** shows the main topics on algorithms, covered in the lectures delivered to the designers and engineers of the researched company. **Appendix J** details the approaches on Management toward Collaboration adopted by Semler (1993) at SEMCO.

2. CONCEPTUAL BACKGROUND

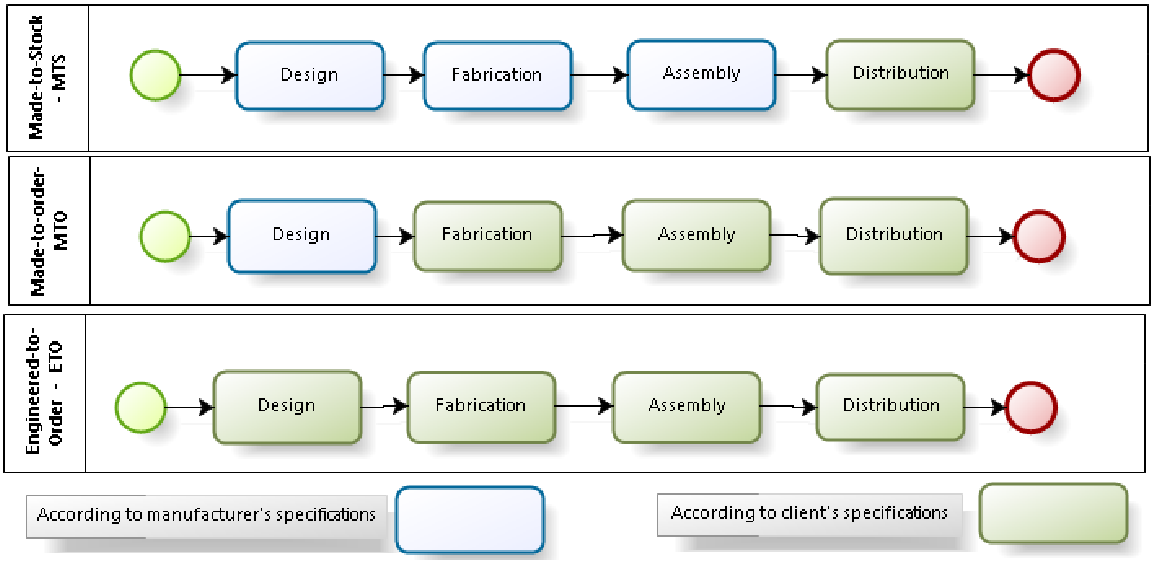
The building components manufacturing systems, according to Swierczek and Kisperska-Moron (2016), Larsson et al. (2016), Leseure (2015), Brodetskaia, Sacks and Shapira (2013), Li and Becerik-Gerber (2011), Eastman et al. (2008) and Ergen et al. (2006), can be classified into three groups, based on the degree of engineering required. These three groups are presented in Figure 1, they are: made-to-stock, made-to-order, and engineered-to-order[2]. Made-to-stock (MTS), also called off-the-shelf, are products fabricated prior to the client's order. For MTS components, the customer's need is fulfilled in the shipment stage. Made-to-order (MTO) are prefabricated according to an existing design. For MTO components, the customer's need is fulfilled in the fabrication stage. Engineered-to-order (ETO) is the design, fabrication and assembly of a one-of-a-kind product. For ETO components, the customer's need is fulfilled as early as the design phase. Engineered-to-order operation is typical for small and medium-sized companies. ETO components specifications are more demanding and more vulnerable to ineffective sharing of information between site and factory, therefore, they are more management-intensive. Custom kitchens, structural steel frames, structural pre-cast concrete, HVAC duct parts prefabricated off-site, curtain wall and facade panels are some ETO examples

Eastman et al. (2008) stated that subcontractors and fabricators of ETO components for buildings may have more to gain from BIM than any other participant in the building construction process. This is because increasingly larger proportions of components and systems of the buildings are being pre-assembled or fabricated off-site, and complex buildings require customized design and fabrication of engineered-to-order components. The flow of information for an ETO component fabrication has three major parts: (1) project acquisition which includes tendering and preliminary design; (2) detailed engineering design and shop drawings; and, (3) fabrication, delivery and installation. In the opinion of Parente, Pegels, and Suresh (2002) the relationship amongst stakeholders is important specifically in an ETO

[2] According to Haug, Ladeby, and Edwards (2009), ETO is "...products which are engineered to the specific requirements of the customer". Eastman et al., (2008, page 246) also define ETO as "...any component customized to fit a specific location and fulfill certain building function"

fabricator's context.

Figure 1 - Building components manufacturing systems



Source: The author.

Swierczek and Kisperska-Moron (2016) studied the characteristics of manufacturing companies that work in a network of organizations held together by trust, cooperation, and information technology. They found that those companies do not offer engineered-to-order products. Engineering to order operation is mostly found in small and medium-sized companies without adequate conditions to increase the investments needed to improve the quality of processes and products.

There are some other concerns in typical ETO fabrication. Besides the inherent demand for more sophisticated engineering, the ETO fabrication is labor intense, controlled by longer production cycle than the production cycle of Made-to-stock or Made-to-order components, and the drawings have high rates of inaccuracies and inconsistencies. Eastman et al. (2008) point out some BIM benefits for subcontractors and fabricators that can address these specific issues in several ways. In the Marketing and Tendering phase, the development of multiple design alternatives, with a reasonable degree of details and measurement of quantities, can reduce the cost of tendering, which is a significant part of an ETO fabricator's overhead. Shorter lead times can be achieved because shop drawings can be generated later in the manufacturing process, and then, clients are allowed to make late changes. Design coordination conflicts can be reduced by detailed design being performed in parallel and within a collaborative work. Lower costs of engineering and detailing can be achieved through reduced rework and automated production of drawings and bill of materials[3]. Automated manufacturing can be increased, because BIM provides automated code for CNC machines, therefore, reducing the human labor necessary to set up the machines. Finally, prefabrication and preassembly can be improved because parts fit properly.

Because accurate and reliable information is critical to the process of fabrication, Eastman et al. (2008) point out five generic BIM system requirements that all ETO component fabricator should demand from any software they take into consideration. The first requirement is the ability to automate parametric design and detailing, nesting components according to pre-defined rules and constraints. The second requirement is the ability to automatically generate production information such as shop drawings and CNC machinery instructions. The third requirement is the ability to provide an interface with purchase, production control, shipping, and accounting. The fourth requirement is the ability to import information from the building designers, general contractors, and other fabricators. Finally, the fifth requirement is the ability to provide effective communication with stakeholders outside the fabricator's organization such as suppliers and components installers.

Adopting BIM in a fabrication operation has an impact on process and people. BIM does not automate existing operations but enables new workflow and processes. Therefore, it requires a strategy that goes beyond software, hardware, and staff training. It should be a thorough plan aiming to get the staff involved and committed from the early stages of the process. In the opinion of Eastman et al. (2008), this strategy, shown in Figure 2, contains four intercepting stages that are described as follows: (1) Setting appropriate goals with measurable milestones. (2) Planning adoption activities dealing with timing and personal commitment. (3) Planning the pace of change with the necessary hardware and software. (4) BIM adoption success requires that people assigned to the new roles have the proper skills.

The first stage should consider the desired BIM benefits, the level of model detail required for tendering, design and fabrication, how, when and by whom the components library is created, the information flow and the integration with

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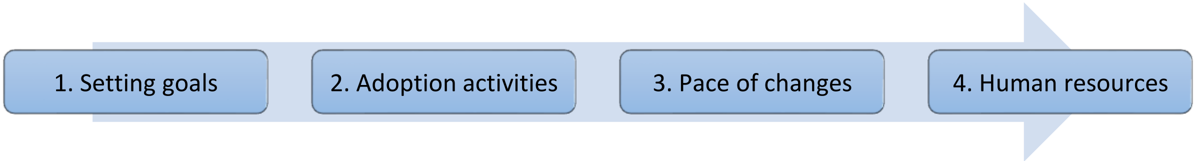
[3] With regard to bill of materials, Neuman et al. (2015), stated that "ETO materials usually have more detailed requirements, which influence their purchase, design, fabrication and installations."

management systems. The second stage should take into consideration the training for the staff, the software customization, and a plan to modeling a project in parallel with the current CAD system. The third stage should take into account a schedule of the adoption costs as well as a phased plan for replacement of existing CAD workstations to BIM workstations. This replacement plan should carry the personnel and hardware needed throughout the adoption process. The fourth stage should consider the effects in the longer term on business and personnel in order to ensure the commitment of the staff and the assigning of the right person to each new role.

Figure 2 - BIM adoption strategy for subcontractors and fabricators



Source: Based on Eastman et al. (2008).

Khalili-Araghi and Kolarevic (2016) stated that customers want to purchase homes individualized according to their needs, but homebuilders want to maintain standardized designs and processes in order to maintain the efficiency of their systems. BIM allows a trade-off between customization and standardization providing the benefits from both strategies. According to Eastman et al. (2008), BIM encompasses a virtual model of a building, carrying accurate geometry, and relevant data needed to support the construction, fabrication and purchase activities needed to accomplish the building and its components. Especially for subcontractors and fabricators, BIM supports a collaborative process for the development of conceptual design and fabrication detailing. Furthermore, BIM allows for essential changes in processes. These characteristics provide the power to manage the vast amount of information required of mass customization[4]. Neuman et al. (2015) stated that customized products have more complex design, engineering, fabrication, and installation requirements.

As stated by Swierczek and Kisperska-Moron (2016), companies within the engineered-to-order manufacturing system, are the ones that deliver highly customized products. In the opinion of Kieran and Timberlake (2004), Mass

[4] Mass Customization: Production of custom-tailored goods or services to meet consumers' needs at near mass production prices (businessdictionary.com on 2016,March,3rd)

Customization is a hybrid of customization and mass production. Mass Customization proposes new processes to build using automated production with the ability to differentiate each artifact[5] from those that are fabricated before and after. As stated by Stralen (2015), shifting the project's focus from the object to processes increases the potential for customization. This can be achieved through digital design and fabrication that enhances communication amongst stakeholders.

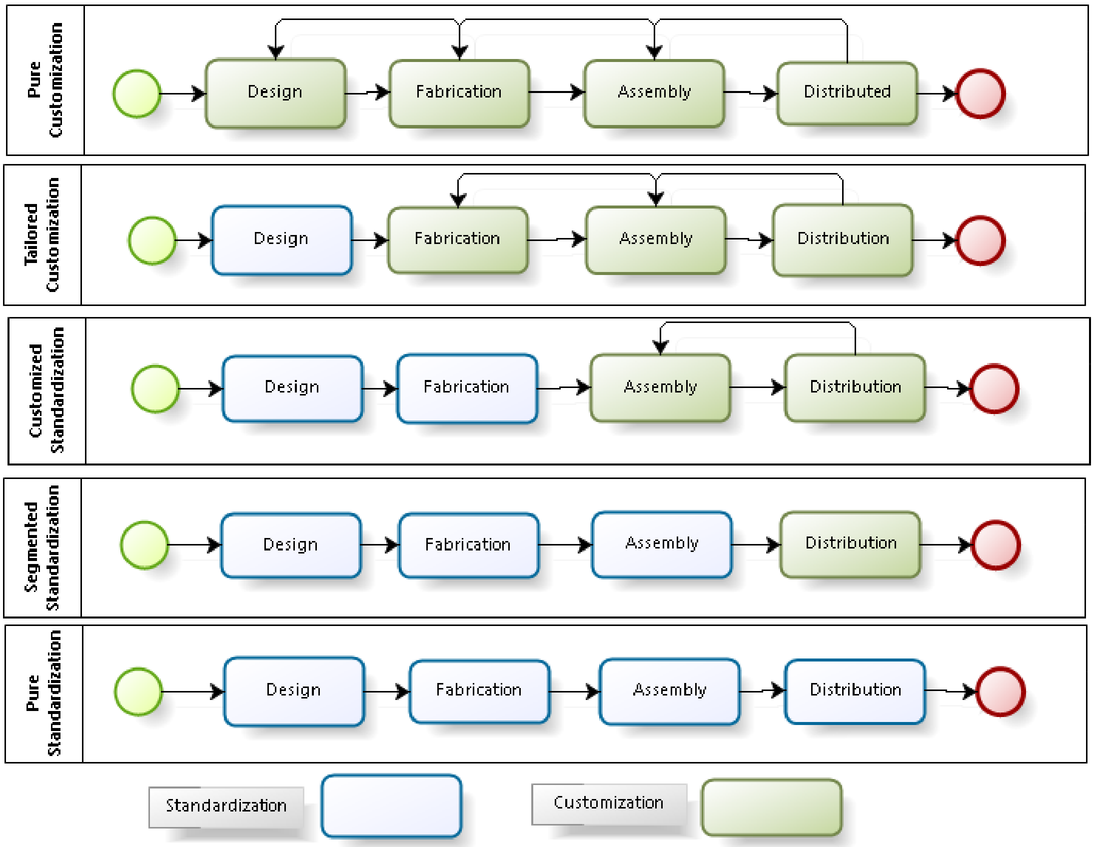
According to Farr, Poorang, and Robinson (2014), Mass Customization denotes an offering that meets the demands of each custumer but can be produced with the mass production efficiency, low-cost and high volume. Khalili-Araghi and Kolarevic (2016) say that the roots of mass customization date back to 1970 when Alvin Toffler asserted in his book *Future Shock* that future technologies would be capable of providing customized products with prices almost to those of standardized products. But Duray et al. (2000) said that it was Stanley Davis who coined the term “mass customization”. In his 1987 book, *Future Perfect,* Davis said that existing technology was a constraint for mass-customized products, but it would prevail in the future. He stated that the more a company can deliver customized goods on a mass production basis, the greater is the advantage over its competitor. Kieran and Timberlake (2004) assert that mass production was the ideal of the early twentieth century and Mass Customization is the emerged reality of the twenty-first century.

Lampel and Mintzberg (1996) described the concept of Continuum Strategies considering a manufacturing company with four stages in its value chain: Design, Fabrication, Assembly, and Distribution. As represented in Figure 3, in the manufacturing process each stage can be standardized or customized to a single customer's needs. The extent to which the Design, Fabrication, Assembly, and Distribution are customized gives rise to five different strategies in which customization begins with downstream activities, closest to the marketplace and spread upstream closest to design, while standardization begins with design and spreads downstream. The five strategies are Pure Customization, Tailored Standardization, Customized Standardization, Segmented Standardization, and Pure Standardization. As described in Table 1, they range from Pure Customization where each manufacturing stage is customized to Pure Standardization where each

[5] Artifact: Something created by humans for a practical purpose. A product of artificial character (as in a scientific test) due usually to human agency. Types of artifacts: Constructs (concepts), Models, Methods, Instantiations and Design propositions. (Simon, 1996)

manufacturing stage is standardized and there is no way of fulfilling a single customer's need. Therefore, companies that offer Mass Customization can do it in four levels: The lower Mass Customization level corresponds to the Segmented Standardization manufacturing strategy where only the Distribution stage is customized. The second level of Mass Customization is the Customized Standardization strategy that offers customization in the Assembly and Distribution stages. The third level of Mass Customization is the Tailored Standardization that offers customization in Fabrication, Assembly and Distribution stages, and finally, the upper level the Pure Customization that offers customization in all four stages of the manufacturing process.

Figure 3 - A Continuum of Manufacturing Strategies



Source: Lampel and Mintzberg (1996).

According to Newman et. al. (2014), the technology of the computer numerically controllers (CNC) machines has a major significance in the manufacturing industry, but an issue regarding the interoperability between CNC machines and the computers used for design is that CNC machines are built with proprietary programmable logic controllers. Over the last decade, a standard entitled STEP-NC has been developed, but the inherent complexity of CNC controllers compatible with STEP-NC, have demonstrated that a fully interoperable STEP-NC system is still a long way to go. Besides this complexity, Newman et. al. (2014), stated that a major barrier for interoperability is the resistance from software developers and hardware makers, who see the lack of standards as a way to maintain their market share.

An engineered-to-order components fabrication is a step toward the adoption of a Pure Customization manufacturing strategy in which the design stage is customized and is the highest level of Mass Customization. In the opinion of Kieran and Timberlake (2004), with information control tools it is possible to visualize and manage off-site design, fabrication, and assembly of mass customized architecture.

Table 1 - A Continuum of Manufacturing Strategies

Pure customization	The product is engineered-to-order. The design is made to the customer’s specifications.
Tailored customization	Small modifications are made to a standard design to adapt it to the client's needs. Only the fabrication, assembly and distribution are customized
Customized standardization	Customized products are assembled from a range of available standardized components or modules. Only the assembly and distribution are customized.
Segmented standardization	A basic design is modified anticipating trends and offering various options, but not an individual choice. Only the distribution is customized.
Pure standardization	Customers must choose amongst the standard products offered. The entire manufacturing process is standardized

Source: Based on Lampel and Mintzberg (1996).

According to Kieran and Timberlake (2004), that which distinguishes the automotive, shipbuilding and aircraft industries from architecture are basically the processes and materials. In construction, architects are happy when they achieve one centimeter of tolerance, while in the automotive industry, precision is measured in millimeters. In their opinion, Le Corbusier saw great promise in the production of architecture by machines. In the AEC industry, computers are being explored not only as a modeling tool. They are already being used as a manufacturing tool, helping to break down the barriers between design and manufacturing and to bring to the AEC industry, the precision measured in millimeters.

According to Gattas and You (2015), digital fabrication relates to technologies that can be used to manufacture building components from automated workshop machines such as CNC routers or laser-cutters. In the process of integration between Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), the production of standardized building components through automated machines have become widely adopted.

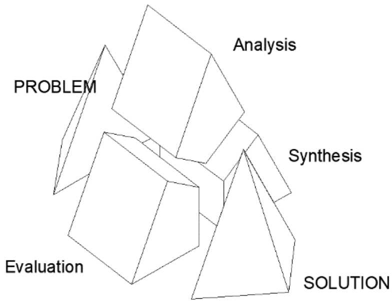
But not so, in engineered-to-order fabrication strategy, because, as reported by Leon et.al. (2013), CNC machines require considerable efforts and expertise in the setup and programming process, before bringing the machine into production.

As stated by Kieran and Timberlake (2004), aircraft production is based on modules that are fabricated in several locations and put together at the final assembly. In the shipbuilding industry, small blocks are nested within larger blocks. The supply chain in the automotive industry has several levels. The assembler subcontracts large modules of a vehicle, and the subcontractors, in turn, hire the production of smaller parts of their modules. This process continues until a chunk is reduced to pure parts.

In the architecture industry, clients are demanding more quality and added features in the scope for less cost and time consumed. Companies have adopted quality management systems such as ISO 9001, but Neuman et al. (2015), stated that those certifications not necessarily improve quality, especially in those companies who offer engineered-to-order products. Quality issues in the design and production of buildings and its components, in the opinion of Kieran and Timberlake (2004), are related to the stratification of the disciplines. Luth (2011) added that throughout history buildings have been produced in an integrated process of design and construction, and the replacement of the master-builder, who was architect, engineer, and constructor, with stratified disciplines is a practice developed in the past century. This trend in the last century has been disruptive to the quality in the AEC industry. Luth continues, stating that this fragmentation on the AEC industry, jeopardizes the success of the projects and makes the interoperability among BIM models very complex. According to him, the current IFC schema is becoming stuck with graphical representations of database objects.

According to Lawson (2006), the design is a dialog between problem and solution through analysis, synthesis, and evaluation as illustrated in Figure 4. Analysis is a breakdown structure, looking for order and patterns of the problem, and for identification and classification of the objectives that the solution must attend. Synthesis is the attempt to link parts of the objects that were detailed in the analysis, toward finding a solution to the problem. Evaluation is a critical thought that compares the solutions found in the synthesis, with the objectives identified in the analysis. The figure, although a very simplified simplification, shows clearly that there is no starting or finishing points on the design process, or even direction of flow among analysis, synthesis, and evaluation. These three, are linked in a cyclical process.

Figure 4 - A simplification of the complex mental process of design



Source: Lawson (2006).

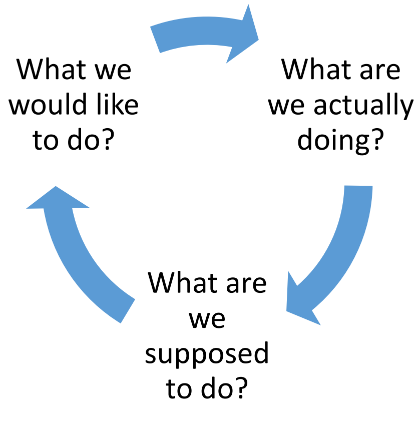
Although designers are often portrayed as highly creative individuals, Lawson (2006) says that the individual is mostly a member of a group. The design depends on individual talent and creativity, but also in sharing and supporting common ideas of a group. Collaboration is in the root of the design. Controlling the balance between the individual idea and the work in groups is wisdom. Design involves a wide variety of human challenges. It requires finding and solving a problem, based on the deduction, inference, induction, abduction, analysis, and synthesis. It requires a balanced decision based on judgments.

Even though the client may have an important role in the design process of an architectural project, the client also has the right to be advised of his or her ignorance when it is needed. Constraints in design can come from a designer, client, user, legislators, or regulatory bodies, but Lawson (2006) says that the many constraints in design comes from the client.

According to Lawson (2006), design involves human communication skills. A collaborative relationship among members of a group may help them to answer the cyclical questions shown in Figure 5. The answers to these questions can come from clients, users, regulation bodies, and from documents of a company. Actual practices are highlighted, implementation activities can be performed and aspirations and wishes may be identified. Lawson states that in a design process many things must happen and the problem and solution may emerge together.

As shown in Figure 6, architects, engineers and fabricators emphasize different aspects, therefore, there is no collective knowledge. Models integrating design and production must be developed. Production has to become part of the design as fabricators get involved at the beginning of the process. The design has to become part of the production as designers think about how things are made and assembled. Designers and fabricators must be members of a team. Kieran and Timberlake (2004) stated, as shown in Figure 7, that architecture specialists need to cross their traditional roles' boundaries, which can be done with the help of Information Technology through interactive tools that provide realtime information and as an outcome, the integration between the stratified disciplines. This point of view is also shared by Luth (2011) that developed the concept of "engineering continuum", in which a building throughout its entire life cycle has a continuous sequence of not apparently different elements both from construction and design. Luth declares that the adoption of a universal database schema should mark the development of new methods in the AEC industry.

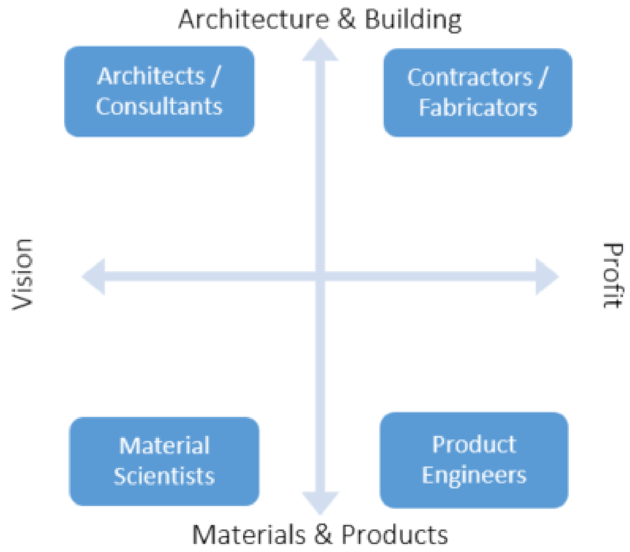
Figure 5 - Questions relevant to the design process



Source: The author.

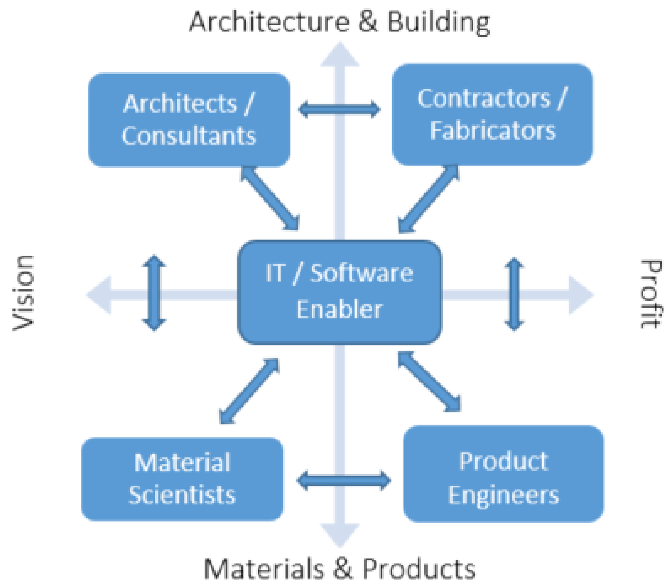
According to Shelden (2014), the proliferation of affordable computing has transformed the capability of architecture to deal with complex forms and details. Although the architecture is going through a deep transition, there remains an essential mismatch between the overflow of digital information and the limits on digital fabrication. Issa (2013) claims that although designers might not need to use mathematical concepts like vectors, matrix, parametric curves, line and plane equations, this knowledge is useful for designers to understand what is happening behind the scene in computational design. The knowledge of mathematical concepts as well as of web database applications may help to ease the communication between designers, constructors, and fabricators. In January of 2015, this researcher saw at the Toronto Pearson International Airport, Canada, a sign that read: “*In the future, the export will be transmitted, not transported*”. This statement points out the internet as a mechanism capable to improve the design and production process of fabrication of building components.

Figure 6 - Stratification and Segregation of architecture



Source: Kieran and Timberlake (2004).

Figure 7 - Enabling collective intelligence



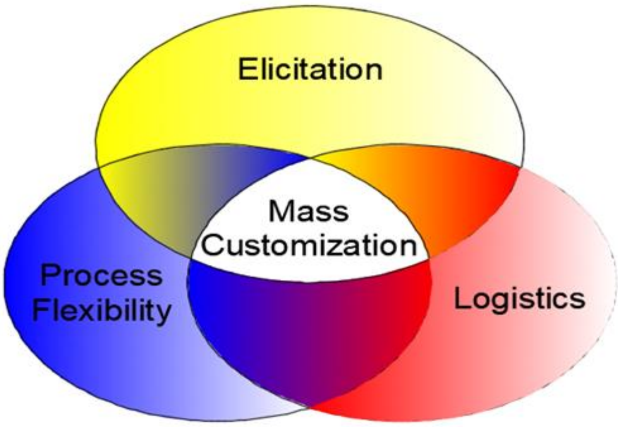
Source: Kieran and Timberlake (2004).

In the opinion of Farr, Piroozfar, and Robinson (2014), web database applications can be expected to be helpful tools together with BIM for facilitating mass customization in the AEC industry. Leiner et al. (2017), stated that the Internet is a worldwide broadcasting mechanism for information dissemination, collaboration, and interaction. According to Tittel and James (1997), Tim Berners-Lee, who played a large role in designing the web, stated that *"The world-wide-web is conceived as a seamless world in which ALL information, from any source, can be accessed in a consistent and simple way*". HyperText Markup Language (HTML), a worldwide standard tool used to build web pages, according to Tittel and James (1997), is a straightforward programming language having a short learning curve. Therefore, HTML makes it possible for every professional in the building construction industry to create useful webpages with easy communication between disciplines. The interface between HTML and databases are provided by Hypertext Preprocessor (PHP), that according to Soares (2004), is a powerful open-source programming language, worldwide used for database access in web sites. s is one of the most used Relational databases in the web environment, that uses the Structured Query Language – SQL. But MySQL is no longer a free open-source database and MariaDB is a free Open-source database created by the same programmers who developed MySQL. In the opinion of Tittel and James (1997), the same web page can be implemented under several different strategies to reflect the specific needs and objectives of small, medium and large corporations, that is, each organization can decide how to publish their web page, either setting up its own server or hiring an internet server.

2.1. Mass Customization Limits and Cautiousness

According to Zipkin (2001), Mass customization has some limits and should be approached cautiously. The limits of Mass Customization are: (1) MC requires a production system very flexible, and the development of the technology required for some processes can be expensive and time-consuming. (2) it requires an efficient system for interaction with the clients to understand their needs and desires, and this is not an easy task. (3) It requires a well-defined system to deliver the right product to the right client at the right time. (4) Customers demand variety, but they are not willing to pay for the high cost of production linked to the customization of a great number of parameters. Therefore, the company must determine carefully which attributes of a product can be customized. In order to advance toward the Mass Customization strategy, Zipkin points three main elements that are interconnected and integrated into a seamless whole as shown in Figure 8. They are Elicitation, Process Flexibility, and logistics.

Figure 8 - Zipkin's elements of Mass Customization



Source: The author.

Elicitation is the mechanism for interaction with the customer, obtaining specific, intelligent information for the design. Extracted information in mass customization systems can be of many kinds: Customer' Identification, Customer' selections, physical measurements and/or reactions to prototypes. Customers often are unsure about what they want and have difficulty in deciding what they want and to communicate their decision. They are easily overwhelmed by too many selections. An elicitation has to lead the customers through the process of identifying exactly what they want. It is worth noting that the deeper the level of customization the more information it requires.

Process Flexibility is how easily information can be translated into the physical product. It is the production technology that fabricates the product according to the information. Process Flexibility is not an easy approach to be achieved, due to the fact that the technology necessary to perform Mass customization is slow in evolving and requires continuing development, but Process Flexibility in Mass Customization must be attained very strictly. It is important to be remembered when planning a production process, that for Mass customization to deliver real value, the attributes that make a product unique must be the ones whose preferences differ sharply from one client to another, and that costs and benefits should be analyzed carefully.

Process Flexibility varies from industry to industry, and, typically, the kind of variety offered to a product depends on the technologies available. Software is as important as hardware in order to achieve Process Flexibility because mass customization gets more complex as the number of spatial dimensions of a product increases, i.e., whether it is a linear, bi-dimensional or three-dimensional object. For example, it is easier to customize a reinforced concrete rebar fabrication process than it is to customize a three-dimensional auto body part using robots that would require high-level software languages.

Logistics is a set of after-fabrication processes, such as transportation and site installation. It is necessary in order to have the final product ready for clients to use. It may encompass a distribution able to maintain the identity of each product and deliver the right one to the right customer. Mass customization has a disadvantage that the customer has to wait for his product, therefore, it requires delivery capabilities that make the process to flow easily. For example, it is necessary that some information moves along with the product through all stages of production, so that the right product reaches the right customer. Therefore, logistic technologies that are basic in e-commerce might also be crucial to Mass Customization, such as the use of companies specialized in delivery.

2.2. Digital Fabrication Techniques

Computers have already been used in every phase of an architectural process. From 3D modeling in the conceptual design, through structural, thermal and energy consumption analyses, and project management. Digital Fabrication comes as one of the final stages in the architectural process. Iwamoto (2009) considers Digital Fabrication as part of the broader concept of CAD/CAM and defines it as the use of digital data to control a fabrication process. Digital Fabrication has been the central component in many other manufacturing industries, for several decades, but not so in the AEC industry. According to Iwamoto, Digital Fabrication is prompting a design revolution in architecture. Iwamoto asserts that Digital Fabrication can be grouped into five types of techniques: Sectioning, Tessellating, Folding, Contouring, and Forming. Those techniques are the ways that can be used to keep a balance between a virtual model in the design phase, and a physical artifact in the fabrication process.

Sectioning is the use of orthographic projections to generate sections of a solid. It's just a process of cutting a 3D object. it is a very effective technique to fabricate complex geometry. The software just cuts parallel sections in the 3D object at designated intervals. The interval can be the thickness of a sheet, for example. This technique is commonly used to create surfaces and structures in airplane and shipbuilding industries and was used by some architects such as Le Corbusier and Oscar Niemeyer before the Digital Fabrication era. The relevance of this technique in the context of Digital Fabrication has less to do with the shape and more to do with the effort needed to fabricate.

Tessellating, also called tiling, is to cover a surface by the repeated use of single shapes that do not overlap either have gaps. They puzzle together in a very tight formation. Tessellation was used in ancient architecture like in the Rome and Islamic empires. In these examples they were handcrafted. Many small pieces were laboriously assembled into a coherent surface in a time-consuming enterprise. The relevance of this technique in the context of Digital technologies has to do with the significant reducing the labor necessary to turn a design into a product. Tessellation allows the smooth building of complex forms like doubly curved surfaces, using simple forms like small sheets. Some examples of the application of tessellating in architecture are brick walls, stained-glass windows, and panelized facades. There are two primary ways used to digitally create tesselation: through NURBS curves and through Meshes. NURBS is a mathematical model used to create smooth curves and Meshes are the use of polygons, usually triangles and quadrilaterals, to create approximately smooth surfaces. Depending on the phase of the design or on the final product desired one method or the other can be used.

Folding is the process of turning a flat surface into a three-dimensional one by bending and flexing a material. It is a powerful technique for creating not only forms but also structures, because when a material is folded it gains rigidity, therefore, it can withstand higher loads and even become self-supporting. Folding is materially economical and effective because new attributes are added to the new object that is being formed without losing the inherent characteristics of the material that is being folded. This technique allows architects to create seamless surfaces, forms, and objects. For example, floors can fold into walls and then into ceilings. Folding has a long history in design and crafts processes. Architects have performed experiments in the twentieth century, especially making formworks for casting concrete generating folded surfaces and curved beams. Folding offers a very great potential for variety in design and fabrication. The fabrication process consists of unfolding a three-dimensional surface in order to make a two-dimensional plate for cutting. As for the Digital Fabrication, modeling software tools usually have embedded the commands necessary for efficiently unfold three-dimensional curved surfaces into two-dimensional ones. Digital Fabrication tools for folding, can enable the design and construction of very complex forms. There is a wide range of software available, which is an indication that folding is a prevailing technique for Digital Fabrication.

Contouring is a process related to carving. Carving, in essence, is removing material from three-dimensional objects and contouring, in essence, is removing material from two-dimensional objects. Though two-dimensional objects have a thickness, which makes them three-dimensional objects, they are considered two-dimensional due to the ratio between the thickness and the other two dimensions. Contouring is a subtractive process of creating a three-dimensional object by successively removing layers of material from a surface. Some examples of materials using for Contouring are plywood, Particleboard, MDF, gypsum boards, and stone slabs. There is a long history of wood, metal, and stone carving in architecture, but Digital Fabrication has enabled architects to bring the Carving and Contouring techniques beyond the handcrafted practice.

Digital Fabrication tools like CNC routers and mills are reviving the use of carved surfaces and ornaments in architecture. There are several types of CNC machines that are commonly used in the fabrication of building components in a mass production environment. These machines are grouped into the two-and-a-half axis, three-axis, and five-axis. This terminology refers to the number of degrees of movement that the machine can translate and the tool can rotate in order to perform the cuts. The two-and-a-half axis machine can translate in the X, Y, and Z directions but can perform cutting operations only in the X and Y directions. The three-axis machine can translate and perform cutting operations in the X, Y, and Z directions. In the five-axis machine, the tool can translate in the X, Y, and Z directions and rotates in two directions. The greater the number of degrees of movement a machine can offer, the more inventive an architect can be, but the fabrication process becomes more complex and expensive. The most commonly used CNC machines in the woodworking industry are the two-and-a-half axis machine.

The Contouring technique requires the translation of a digital model into a language that the computer in the CNC machine can understand. The common language used to program the CNC machines is called G-Code[6]. G-code is a low programming level language that comprises a set of individual commands. Each command is listed on a separate line of code that begins with the letter G. In order to make it easier the CNC machine programming, CNC makers have provided graphical interface programming environments, but each CNC maker has developed his own proprietary language. Those languages provide a more friendly environment for the programmer, but this can be a problem regarding the interoperability between the design software tools and the fabrication machine software because each CNC machine has its own language. Depending on the features of the CNC machine it has specific sets of variables that must be defined. Some of them are the characteristics of the tools, the speeds, the material being cut, and the path the tool must follow. Contouring is inherently a technique with high material usage and time-consuming. It is a process that has a great deal with material waste. Therefore, material leftovers must receive special attention in the design process.

[6] G-CODE stands for “Geometric Code”. G-Codes are a set of instructions that tells a CNC machine where and how to move. It also sets up the machine environment, like positioning, coordinate system, speeds, and tooling.

Forming is a plastic deformation of materials to produce the desired shape and generate multiple components from a small number of formworks. The most common use for this technique is the fabrication of products in a mass production environment. Façade panels and window mullions are some examples of building components that can be fabricated by forming. Engineered-to-order building components can also be fabricated using the forming technique. some examples are precast panels and cast-in-place slabs. Forming is a technique that offers efficiency by reducing the amount of formwork necessary in the fabrication of multiple similar parts. Mass-produced building components may have the disadvantage of repetitive overall patterns, and the components fabricated under the engineered-to-order strategy may have the disadvantage of high cost and time- consuming manufacturing process. Digital Fabrication has brought new possibilities for conceiving unique, low cost and rapid fabrication of building components.

2.3. Projective Geometry in Parametric Modeling Context

According to Hartley and Zisserman (2003), projective geometry is a group of techniques for drawing complex intersecting objects in several views. Projective geometry was developed throughout the 19th century, taught extensively in the first half of the 20th century in schools of engineering and architecture (SAKAROVITCH, 2009). In the last half of the 20th century, projective geometry was little by little being taken from the curriculum of the schools of architecture and engineering as an explicit discipline (GOLDSMITH et al. 2014) and (YILMAZ, 1999). By the end of the 20th century, drawings were made by CAD systems, based on a very simple idea called Snapping. Snap is a technique in which the software recognizes some predetermined geometric places in an object such as a midpoint, endpoint, intersection, or a center. Snap took the role of the traditional compass and straight-edge tools. But designers still need to master the concepts of projective geometry to do their work (PARVEZ, 2018).

Parametric modeling is to combine geometry, symbols, and algorithms in order to represent objects and how these objects are related to each other. New tools are always being developed but they rely on points, vectors, and operations of points with vectors and between vectors. Mathematically, and algorithmically, points and vectors are represented as one-dimensional matrices. The arithmetic of vectors[7], points[8], and operations with lines and planes are used to create parametric equations both in two-dimensional and three-dimensional constructions. After vectors and points, lines in two-dimensional space, and planes in three-dimensional space are the most basic spatial objects (Anton and Tanase, 2016).

Parametric modeling tools allow the designers to apply their knowledge of projective geometry in more complex constructions (MONEDERO, 2000). Woodbury (2010) highlights three main differences in the way that designers uses projective geometry in parametric modeling tools if compared with traditional tools. The first difference lies in the persistence of constraints which means that once an object is placed in the model, parameters keep the control of that object even after the object is changed. A second difference is that there are more diversity and plenty of tools. Each tool is specialized in a specific task. The designer has to master several different tools. The third difference is that due to the fact that tools are specific and specialized, though existing in large quantity and diversified, designers at some point are constrained by the tool unless he decides to delve into the domain of computer programmers.

Mastering parametric modeling tools requires a different kind of geometric knowledge than the knowledge that was required from previous generations of architects. They now must be skilled in predict persistent effects, understand the mathematical structure of each tool that they use, and be able to link intention with mathematics. But the basic knowledge that architects must have are the concepts of point and vectors, which are the fundamental objects upon which the three-dimensional operations are performed (BEESLEY, WILLIAMSON and WOODBURY, 2006). Points and vectors are the geometric foundation of the parametric modeling tools (PAULY, 2003). Geometrically, the point is a position in space and vector is a direction and a length (PARVEZ, 2018).

Besides mastering projective geometry and parametric tools, designers must frequently remember to apply the right-hand rule to define the orientation of the coordinate system and the directions that their objects are going to move, and the

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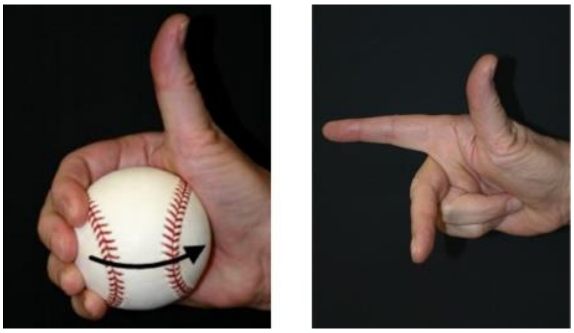
[7] Arithmetic of vectors: addition, scalr multiplication, inverse, multiplication of vectors
[8] Arithmetic of points: the subtraction between two points is a vector and the addition of a point and a vector is a point

right-hand rule of rotation, which define the positive rotation around an axis. Two straightforward rules that can simplify a very complex spatial reality when creating and modifying parametric models. As illustrated in Figure 9, the designer can point his thumb finger in the positive direction of the axis, and his curled fingers point the positive directions of rotation around the same axis. For the orientation of the coordinate system, the index finger points to the X-axis, the middle finger points the Y axis, and the thumb points Z-axis (Bahill and Baldwin, 2007).

Figure 9 - Right-hand rules to define orientation and rotation



Source: Bahill and Baldwin (2007).

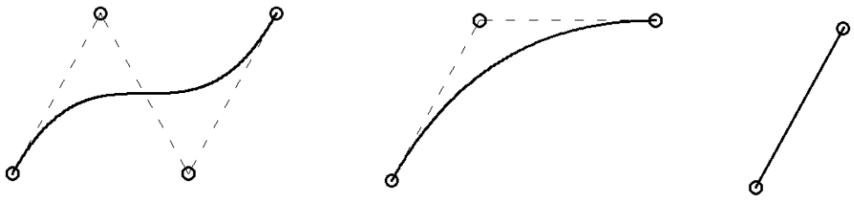
In addition to learning about vectors and points, as part of the skills needed for mastering projective geometry and parametric tools, Woodbury (2010) adds the knowledge of explicit and implicit equations of lines and planes in two-dimensional and three-dimensional spaces, operations with lines and planes, parametric equations for lines and planes. Woodbury also names the knowledge in generating, representing, mapping and transforming matrices. Lines and planes are relatively simple to represent, construct, and to fabricate objects based on them. But the real world has plenty of curved surfaces and solids, which makes the fabrication of a simple ship hull, a very complex task. Therefore, besides all the previously geometric knowledge mentioned, designers need to have knowledge in conic sections, representation of parametric curves, relating objects to curves, the intersection of curves, and the understanding of the concepts of Bézier curves, B-Spline, order, and degree of a curve. Bézier is a class of curves constructed from polynomials. A polynomial is a sum of monomials. A monomial is a product of constants and variables raised to a positive integer exponent. For instance, Table 2 exemplifies some monomials and polynomials. The degree is the maximum exponent in the polynomial, and order is the degree plus 1. Bézier curves are curves controlled by some points called vertices. The quantity of vertices that controls a curve gives the order and degree of a Bézier curve. The first curve shown in Figure 10 has order 4 because it is controlled by four points, and degree 3 because it is generated by the polynomial $aX^3 + bX^2 + cX + d$. a simple line is actually a Bézier curve which has order 2 because it is controlled by two points and degree 1 because it is generated by the polynomial $aX + b$

Table 2 - Polynomials and their respective order

POLYNOMIAL	DEGREE	ORDER
$aX + b$	1	2
$aX^2 + bX + c$	2	3
$aX^3 + bX^2 + cX + d$	3	4

Source: The author.

Figure 10 - Order and degree of Bezier curves



Source: Woodbury (2010).

Parametric modeling allows designers to make a complex design with precise control of connections between components, which in turn can be controlled by numerical, textual or logic parameters. One of the greatest benefits of parametric modeling is the simultaneous manipulation of several components. The parametric links between components give the designer more freedom to discover new ideas because one action can trigger several other actions. More modeling power tools have already given the designers the opportunity for great innovations, but the processes of fabrication still are some of the constraints and limitations in transforming a virtual model into a real object or a component for a building (WOODBURY, 2010).

2.4. Computer Programming in Parametric Modeling Context

Programming is embedded in parametric modeling. Therefore, in the field of parametric design, mastering programming is a recommended skill for designers; at least the basic knowledge of algorithms. Algorithms are written for the purpose of communicating with the computer with precise language. The best way to learn this skill is to work intensively and to the exhaustion with a programming language, just like the most effective way to learn a spoken language is to immerse oneself among natives of a country where the language is spoken. Programming is a skill that is learned in sequential stages, and every stage relies on concepts learned in previous stages. In each stage, the student builds cumulatively ability to program, typically short programs. In fact, every programming language is basically the materialization of the general concepts of algorithms. Therefore, prior to learning a programming language, it is better to learn those concepts which are values, variables, expressions, statements, control statements, functions, types, objects, classes, and methods, as detailed in Table 3.

A variable must have a name and a good programmer chooses the name that best represents the value it holds. Nodes in a graph are corresponding to variables in programming. Expressions are the basic unit to build an algorithm. There is a special statement called “assignment” which is to assign a value or a result of the evaluation of an expression to a variable. A set of variables, expressions and a sequence of statements can be used for the creation of a simple form of an algorithm. The simpler control statement is the “if” statement which executes a block of code if some condition is true or executes another block of code if that condition is false. Other control statements are the ones that allow the repetition of a set of code in a cyclic loop until a certain condition fails or while a certain condition is true. Control statements are useful to make it easier the execution of some actions that may vary according to the values that a variable may have. They are very useful when programming a set of codes that are very similar. Control statements also help to make the code more readable. As the concept of function is introduced, the concept of the variable becomes a little more complex. There are two groups of variables: Local and global variables. Local variables are the ones that exist only inside a function, and global variables exist also outside the function. A good programmer tries to avoid as much as possible the use of global variables because they make a program hard to be understood and debug. Functions are very useful to enable code reuse, but global variables prevent the reuse of functions. Some languages require that a variable must be explicitly declared to be of a specific type before they receive data, while other languages are more generic as to the way it stores the values.

(WOODBURY, 2010).

Table 3 - Computer programming basic concepts

Concept	Description
Value	Piece of data which can be one of several types such as an integer, a string, a boolean (true or false)
Variable	It can be understood as a container that holds a value.
Expression	Combination of variables and values linked by operators such as + - * / < <= .
Statement	Unit of code that a computer can execute. Can be understood as a container who holds a code.
Control statement	Class of statement whose purpose is to control the flow of data through the algorithm.
Function	Block of statements that receives imputs called arguments and have codes that act on the imputs and return values called outputs. It can be understood as a block with a name.
Type	The way the computer stores the data. Can be numbers, characters, strings among others.
Object	Generalization of values. Combination of values into a coherent collection.
Class	Generalization of objects. An object is an instance of a class.
Method	Function specific to a certain class.
Data structure	An ordered collection of cells that have a name. Each cell can be accessed by an index.

Source: Woodbury (2010).

Every geometric object has properties. Dot notation is used to reference property to the object. For example, if “P” is a point object, then “P.X” could be the property holding the X coordinate of this point. The point “P” could also be declared as an object with three properties, the X, Y, and Z coordinates. As an example of a class, in order to generalize the creation of points, a programmer could create a class called “point” with four properties called X, Y, Z, and Visible. This class can be used to declare any number of objects which would automatically inherit those four properties. Lists and Arrays are examples of Data Structures. They are useful to organize data. A Data structure comprises types (or classes) and functions (or methods) that perform coherent operations on objects of these types (or classes). Each cell is accessed by the name of the list or array followed by an index that locates the cell. They are useful in parametric modeling (WOODBURY, 2010).

Objects, classes, methods, and Data structures are more complex concepts that are very important in the context of parametric modeling because they are closely related to the ability to reuse a model and are very helpful for the purpose of making programs more robust and understandable. However, if not clearly understood, they may represent a trap to the programmer. Therefore, for most designers in parametric modeling, the use of simple objects and functions, and the minimum use of classes are often enough to produce excellent results (WOODBURY, 2010).

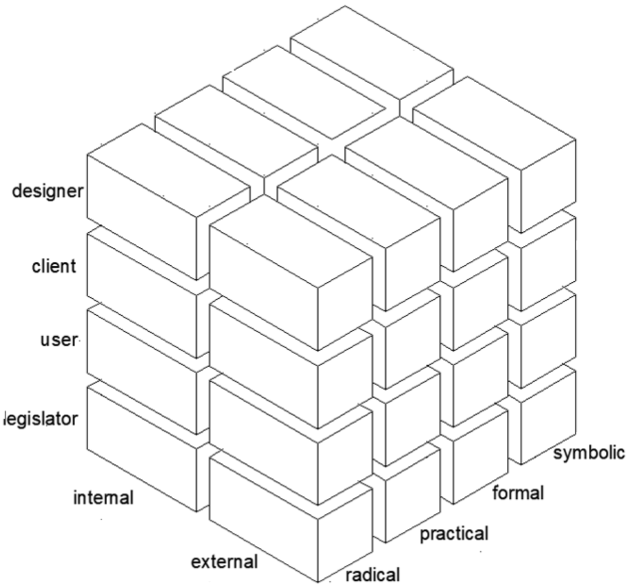
Computer programming is generally learned through a series of examples. Woodbury (2010) suggests a three-step method for learning parametric modeling with patterns: The first step is to learn the basic commands of a tool and create a very simple model. The second step is to break a complex body into simple components. The third step is to create a model for each component. Each component becomes a pattern that interacts toward the modeling of the original complex body.

2.5. Parametric Design

Design problems are established over constraints, and constraints are limits or restrictions that come from requirements or from the desired relationships between some variables or elements. For example, in a kitchen, the legislator may require a minimum space between the cooktop and the upper cabinetry, the client or user may express a wish for two fridges and the fabricator may expect the material to be selected from a predefined catalog. Those are constraints enforced by different stakeholders. In the model of design problems created by Lawson (2006) and presented in Figure 11, there are four stakeholders that generate constraints: clients, users, designers and legislators. A constraint can be internal to the problem and the object that is being designed but can also be an external factor to it, something that is not under the control of the designer. The purpose of the constraints is to ensure that the designed object correctly performs its required functions. Lawson adopted four roles for the constraints: radical, practical, formal, and symbolic.

Internal constraints are entirely situated inside the problem, they are inner parts of the problem. In architectural design, they may comprise the number and sizes of spaces and the relationship between these spaces. These relationships can be human circulation or acoustic requirements. External constraints are external to the problem, they connect the object that is being designed to its context. In architectural design, the external constraints can be the relation of the building with the sun or with a neighbor site. The external constraint may come from the manufacturing process, the properties or availability of materials, or even by the transportation of the product from shop to the job site. Internal constraints generally allow a greater degree of freedom and options of choice to the designer than external constraints. Internal constraints are more evident, easy to understand, and easy to be expressed by clients than external constraints. Internal constraints are more flexible and external constraints are more rigid (LAWSON, 2006).

Figure 11 - A model of design problems



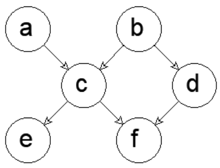
Source: Lawson (2006).

The radical constraint deals with the primary and basic roles of the designed object. This kind of constraint is very influential in the design process because they are the reason for the design. Practical constraints deal with the environment of the design process, with the manufacturing process of the object, and with the performance of the object during its lifecycle. Formal constraints are related to the visual aspects of the object, like proportions, form, color, and texture. Symbolic constraints address the abstracts properties of the object, like reconnection or contradiction effects that an object may express. Although all four stakeholders in the model generate all four types of constraints, clients and users are the stakeholders that generally generate the radical constraints, and designers mostly are the ones who generate the formal and practical (LAWSON, 2006).

Pencils and erasers are the centuries-old designing tools that were used to add and remove marks but now are emulated by the modern modeling parametric tools which also introduced the coordination of constraints in the modeling. Spreadsheets are still the most used parametric tools, though not geometric systems and despite the large availability of database resources. It is a very simple rectangular table of cells, which makes it easy to be used in many disciplines. According to Woodbury (2010), parametric systems can solve constraint problems in three approaches. The first is the representation in a graph of objects as nodes linked by constraints. A graph divides a problem into sub-problems and the solution of the problem is searched in the recomposition of these sub-problems. The second is a Logic-based approach which describes a problem as an axiom and applies inferences in search for a solution to the problem. The third is an algebraic translation of a problem into a set of equations of constraints, and the solution of a problem relies upon solving those equations.

Graphs are collections of nodes connected by links which have directions. and join predecessor nodes to successor nodes. In parametric modeling, a node is an object that has name and properties and each property has a value. For example, a node for a point can be named P1, some of its properties can be its Cartesian coordinates X, Y, and Z. The coordinates could hold the values 2,4 and 5 respectively. The graph illustrated in Figure 12 is a well-formed graph. A sequence from a node without predecessor until a node without successor is a chain. To create an algorithm is to put an order in a graph. As an example, Figure 12 illustrates an algorithm in which every predecessor node for each node in the graph occurs before the node in its sequence (WOODBURY, 2010).

Figure 12 - Schematic representation of a well-formed graph



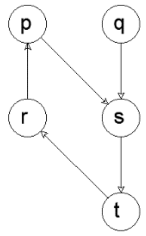
Source: Woodbury (2010).

In a graph with cycles, as can be observed in the sequence (p, s, t, r) in Figure 13, a node becomes the predecessor of itself. If an algorithm is applied to this graph, it performs an infinite loop. Parametric design is a graph that has no cycles. Figure 14 is an example of a cyclic graph in a spreadsheet. This should be avoided at all costs but the chances of this happening increase in geometric proportion with the degree of complexity of an algorithm. As the figure shows, the software displays a warning message that alerts the user regarding a cyclic reference. If the user disregards the warning and continues the work as exemplified in Figure 15 it still performs an infinite loop, which is the characteristic of a cyclic graph. Figure 12 could be a representation of parametric design because it has no cycles. In parametric modeling, the designer characterizes the information needed in order to create the model, collects data and sorts the information from the known to the unknown. Then he creates a graph, identifies the sequences and creates algorithms. A constraint is a formula comprising objects, functions, operators, and results. For example, sin (30) is a constraint that when evaluated gives 0.5 as the result. In this constraint, the numbers 30 and 0.5 are the objects (WOODBURY, 2010).

A well-formed parametric design is a graph with no cycles and three algorithms. The first orders the nodes in a sequence where each node occurs only after all its predecessors have occurred. The second follows the sequence evaluating the properties of each node. The third displays the results through symbols that can be nodes and links or drawings. If these three algorithms are performed by a computer in less than approximately 1/30 of a second, the designer feels like he is interacting directly with the model. The parametric design of a simple translation of point p to point q is represented in Figure 16 by two graphs and one drawing. The first graph has six nodes and each node has one property which is the cartesian coordinate of one point. The second graph has two nodes and each node has three properties, the three cartesian coordinates of each point, and the drawing shows the translation from point p to point q (WOODBURY, 2010).

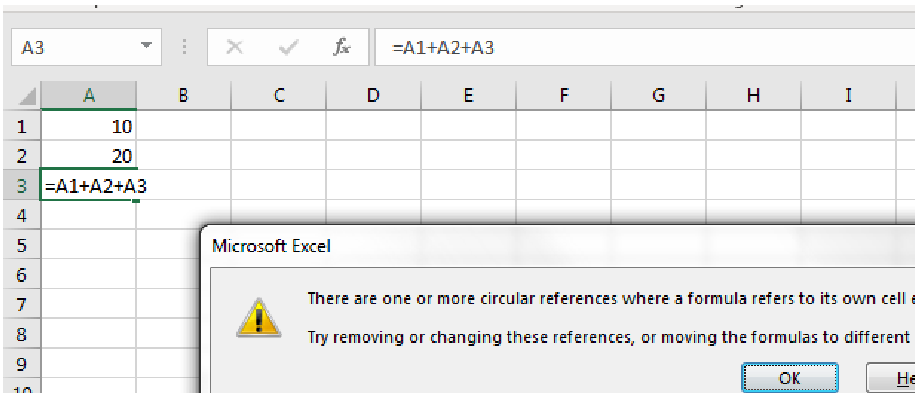
Parametric modeling requires a combination of two techniques: geometric construction and programming. Geometric construction is to make a sequence of simple operations. For example, Figure 17 shows two ways of constructing a tangent from a point to a circle. Programming is to build a model by writing algorithms. It requires the skills of analytical geometry. For example, the parametric programming of the translation of point p to point q shown in Figure 16 could be written as $p(x, y, z) \rightarrow q(x+a, y+b, z+c)$ (WOODBURY, 2010).

Figure 13 - Schematic representation of a cyclic graph



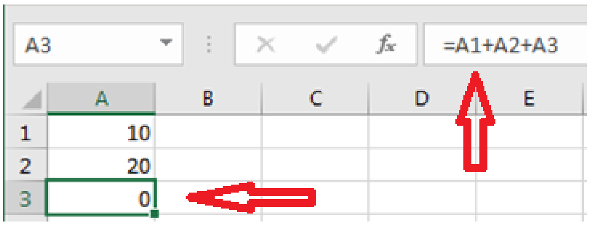
Source: Woodbury (2010).

Figure 14 -Example of a cyclic graph in a spreadsheet



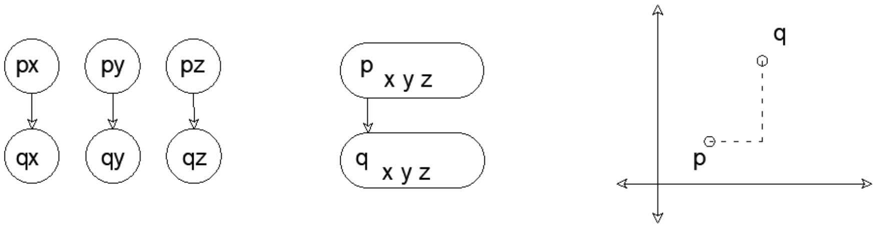
Source: The author.

Figure 15 -An example of a cyclic graph with an infinite loop



Source: The author.

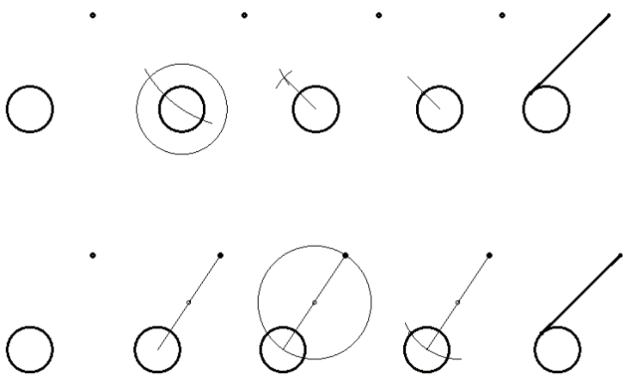
Figure 16 - Parametric design of the translation of point p moving to point q



Source: Woodbury (2010).

Constraints must be expressed before the problem can be solved. Several languages for expressing constraints have been designed. Propagation-based systems are the simplest type of parametric systems. They arrange objects in a directed graph in which known information is placed upward and unknown information is placed downward. The system propagates from the known information toward the unknown. This system is used in spreadsheets, dataflow programming, and CAD systems, due to its simplicity, clarity, speed, and reliability. (WOODBURY, 2010).

Figure 17 - Two construction sequences for a line through a point p and tangent to a circle c.



Source: Woodbury (2010).

According to Woodbury (2010), the parametric design process requires a thorough knowledge of design and computer programming. Since it is hard to be a specialist in both areas, the parametric design should be practiced in a group of specialists. Woodbury says that almost all professionals who use parametric modeling lack formal education in computer programming, but they are the ones who write most of the programs used currently.

Design problems come mostly from clients, but designers also discover problems without a client. A client is a person who is unable to solve or even to understand a problem. In the design process, the client can be represented by a professional or even by a committee. According to Lawson (2006), many architects do not see the client only as the provider of a problem to be solved, but they also see the client as a partner in the process of clarifying the problem and define its constraints. It is certainly naïve to think that a client delivers the designer with a complete description of the problem and the totality of its constraints clearly attached, therefore, the relationship between client and designer can be support or an obstacle in the solution of the problem. In architectural designs, usually, the client is not the user, and the user, most of the times, do not have active participation in the design process. There is a gap in the communication between the client and the user and neither the architect nor the client is aware of this gap. Legislators are the agents that create constraints which designers must follow. These constraints can be some standardizations, codes of practices or only recommendations regarding safety, utility, and appearance. Typically, there is some tension between designers and legislators. A designer may see legislator as inflexible and senseless and legislators may see designers as obstinate and irresponsible (LAWSON, 2006).

In the process of using the traditional CAD tools, it was easier to create a model than to make changes in an existing model. Even the change of a single dimension would require adjusting many other parts. These tools limited the exploration and restricted the design. These limitations would be more critical in the context of customized design that has a more dynamic interaction with clients. Parametric modeling addresses these limitations. In parametric modelling the designer establishes relationships between components and creates a design by using these relationships. This system increases the design freedom to explore ideas, but the previous phase of creating a library of components with embedded constraints and relationships among components would be more complex especially in customized design. Once the library is created, the design becomes the act of creating relationships and editing the constraints. This new way of designing requires new skills from the designers and offers them new design strategies. For example, drawing is a skill, and combining orthographic views or perspectives in order to analyze an idea is a strategy (WOODBURY, 2010).

Six skills are required from designers to master parametric design according to Woodbury (2010). Those skills are the basic ones. The first skill is to know how to identify the nodes and then develop the way in which the data flows through a parametric model, from independent to dependent nodes. The second skill Woodbury calls “dividing to conquer” and this means to organize the work in recursive systems of parts with limited interactions between parts. It is to divide the design into parts and then to combine the parts again analyzing the interactions between the parts. The third skill is to give names wisely to the parameters, for the purpose of facilitating the communication between those who deal with the design and also for the designer to remember his own logic in the future. The fourth skill is to think with abstraction. Designers and computer specialists apply the concept of abstraction slightly differently. For computer specialists, abstraction is to seek formalism and codification in a way that applies in many situations. This is called generalization. For designers, abstraction means to make a model specifically applicable in a new situation. It is to make a model dependent on very few inputs and remove all possible dependencies from external parameters. For both, computer specialists and designers, a well-crafted abstraction is a key part of efficient modeling, because it allows the reuse of a component or graph in several models. The fifth skill is to think mathematically. There is no need for a designer to delve into deriving theorems; designers routinely have used mathematics, as he or she constructs lines and snap them into circles, tangents, and intersections. But modern parametric modeling tools have made available for designers, the possibility to transform into a building, very complex surfaces, tangencies, projections, and planes. Modern tools allow designers to play easily with convex hulls, Voronoi diagrams, and Delawney triangulations. The last skill mentioned by Woodbury is to think algorithmically. An algorithm is a finite procedure with fixed vocabulary and precise instructions that execute step-by-step a complex process. Parametric design is a graph that contains nodes and links. Links are the constraints, nodes are the objects, and both are part of algorithms. With the purpose of expressing their ideas, designers need to write algorithms. Almost all current modeling tools offer programming languages called generically as “script language”.

Nine strategies are available to designers in order to perform parametric design according to Woodbury (2010). The first strategy is sketching. Sketching with paper and pencils is a traditional task performed by designers. For Woodbury, sketches are quick, timely, inexpensive, disposable, generous, and have a clear vocabulary, minimal details, and an appropriate degree of refinement. Most of these characteristics are related to the role of sketches in the design process, and not to the tools used to create the sketch. Therefore, sketches can also be created using modern parametric modeling tools. They are dynamic and can rapidly be changed to reflect ideas and experiments. The second strategy Woodbury calls “Throw code away”. That means that designers just need to create computer codes that are needed for a specific modeling process. They don’t need to intend to make the code reusable and clear aiming to use them in the future. This is OK for a designer’s point of view. To make code clear and reusable is a computer specialist’s prerogative. The third strategy is called “Copy and modify” and is the opposite of the second strategy. Although designers don’t need to worry about creating a clear code like the computer programmers, they are happy when are able to use a clear code made by others and be able to modify them according to their need. The fourth strategy is to search for form. Parametric modeling opens a new world of possibilities for designers. For example, computerized recursive functions can be used to create forms that otherwise would be almost impossible with paper and pencils. Furthermore, a single recursive algorithm structure can produce a wide variety of designs with minor variations in the design process. The fifth strategy is to use mathematics and computation to understand design. For example, sections cut out from a toroidal surface yields a very rich form. The sixth strategy is to “Defer decisions”. Accuracy and precision are mandatory in good design. With the traditional designing tools, once a parameter is defined, it is hard to change it in the future, but with parametric modeling tools, it is very easy to change parameters late in the design process. Indeed, the main argument in favor of parametric modeling is its ability to support rapid changes late in the design process. The seventh strategy is to design using modules. The main use of parametric modeling tools is to reduce the complexity of graphs and to reuse algorithms. Objects and constraints can be encapsulated in a set of independent parameters, which makes them reusable. The eighth strategy is to be willing to help others. This can be done by sharing codes and modeling tasks. The rewarding of sharing is not only fame, but it is also a way of self-mastering parametric modeling technology. The ninth strategy is to develop his or her own toolbox, a set of reusable models and parameterization. Applying these nine strategies, and having the six previously described skills, the designer may create his own powerful toolbox. He can even create new strategies if he develops also some computer programming skills, at least the basic knowledge of algorithms.

Reusable parts are the backbone in parametric design practice, but the abstraction required to create them is the hardest new skill that designers need to develop. Patterns can be helpful to understand and to practice parametric design. A pattern is an explicit, partial (more than a simple node and less than a complete design), focused, and generic solution to a problem that includes the problem, the solution, and other information that explain the context. The most ancient pattern known in the architectural field is the Vitruvius’s *The Ten Books of Architecture*, a text that survived from the Roman times. Woodbury (2010) presented thirteen patterns aiming at helping designers to learn and use propagation-based parametric modeling systems, and to choose design alternatives that make a model reusable. The thirteen patterns are shown in Table 4 and Table 5, with four elements of their structure starting with the Categories they are grouped into followed by the goal behind the pattern, the problem that the pattern intends to solve, and the explanation of the pattern's adoption mechanism. The first pattern is also the first category because *Clear Names* are mandatory for every pattern. The second category encompasses the *Controller, Jig, Increment,* and *Reactor*, which are the basic techniques for structuring a model. In the third category are the *Point Collector* and *Place Holder* which specify the location of objects. The fourth category comprises *Projection, Reporter*, and *Selector*, which are ways to abstract information from models. In the last category are *Mapping, Recursion* and *Goal Seeker* which comprises applications of simple functions toward complex models.

Architects are familiar with abstraction in their work dealing with circulation, light, structure and other architectural tasks, but in order to master parametric design, they must develop a different kind of abstraction that is more related to the mathematical abstractions used by computer programmers. They need the abstraction that allows them to work with reusable complex parts of a model. Software engineers are used to patterns that help them avoid alternatives that threaten the code reusability. Patterns also foster communication, because rather than explaining an idea from scratch, the designer has only to say the name of the pattern and everyone knows what it means.

To write a pattern is to describe what repeats in a predictable way. Patterns may be the outcome from the work of a group of collaborative individuals, toward the creation of a shared library of low-level components for design. Patterns are intended to be easily copied and modified. They provide the means to solve the "conquer" aspect of a "Dividing-to-Conquer" design strategy. Patterns are useful to make clear the data flow through a model, and also helpful in sketchings because they make it easy the creation of preliminary models (WOODBURY, 2010).

Table 4 - Some elements from the patterns for parametric design (Continues)

	Category	WHAT (goal)	WHEN (problem)	HOW (adoption mechanism)
Clear Names	Mandatory	Clear and short names that are easy to be remembered	Always	Put words together with no space and capitalize each word. No linking punctuation
Controller	Model structure	A simple separate model that controls a model or a part of the model	There is a need to simplify tasks in the main model	Build a separate model whose outputs link to the inputs of a main model
Jig		A Framework to isolate and locate geometric detail	Thee is a need to express simple version of structures or to fix locations and paths.	Like construction lines in CAD systems, Jigs are simple versions of a more complex model.
Increment		Drive changes through a series of closely related values	Parts have similar structure but different inputs.	Gradual changes in two forms: discrete if driven by integers, or continual if driven by reals.
Reactor		Make an object be affected by its proximity to another object.	Need to express an object property in terms of the property of another upstream object.	Connect an “interactor” object to act reciprocally with a “reference” object which interacts with a “result” object
Point Collection	Object’s location	Organize collection of points to locate repeating objects.	Artifacts have repeating elements	Locating points in Euclidean coordinates (cartesian, cylindrical or spherical) or in parametric space (curve or surface)
Place Holder		Use representative objects to organize complex inputs	A part has multiple inputs and customizing each one requires a lot of work	First the representative object carries the module inputs, then a code relates the representative object to the module.
Projection	Abstraction of information	Transforms an object that is sent to another geometric context	There is a need to construct a relationship between an object “here” and an object “there”	An object is projected into a receiving object through a Parallel Projection, a Normal Projection, or a Perspective Projection method.
Reporter		Transform data from a model providing data to another model	Using relevant parts of a model is tedious or when there is a need to use some aspects of a model in another part of the model.	Information flows from downstream object to upstream object that feeds back, information to downstream object.

Table 5 - Some elements from the patterns for parametric design (Conclusion)

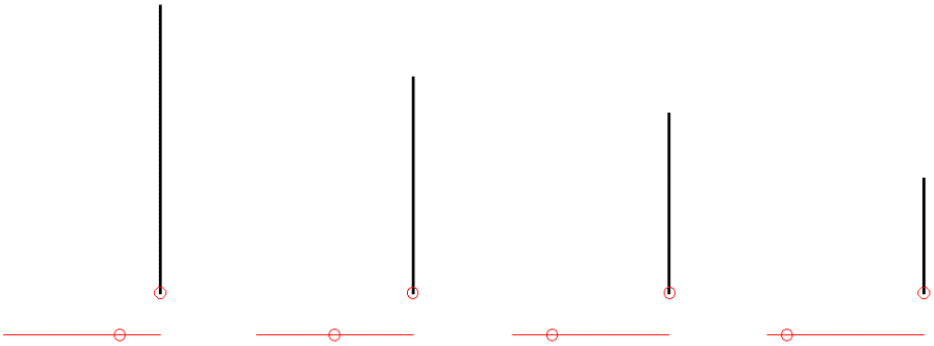
Selector		Select from a collection, elements that have specific properties.	There is a need to update dynamically, a function in a model based on values of some parameters.	To a collection of given objects is applied some conditions to test if they meet certain criteria that allows them to be selected as outcomes.
Mapping	Complex modules through simple functions	Use a function in a new set of input and output values.	A function must be used with input and output values specific to a model.	A function with a specific set of input values is applied to a model with a different set of input and output values.
Recursion		Create a pattern by recursively replicating another pattern.	Properties of a function derives from the function immediately superior to it.	A function uses a replication rule to generate a collection of clones out of a pattern geometric object.
Goal Seeker		Changes an input of a model until a chosen output meets a certain goal	Need to adjust the input of a variable in a model until an output reaches a goal.	An output is evaluated, then an input is adjusted

Source: Adapted from Woodbury (2010).

The more a designer uses patterns made by others, the more he is able to write his own patterns and reuse his design ideas. It takes time and effort to write patterns, but the result is clarity and simplicity in the future. This is mostly a team-work. In order to identify patterns to be created the designer may answer some questions: which are the tasks that are done over and over with small variations? Can these tasks be described with short sentences? The process for writing design patterns starts with collecting samples and finding what they have in common. Then checking the code of each sample to see if they are consistent and make a pattern from them. The next step is to use the pattern in real works. Periodically it has to be refined for more clarity and simplicity. A pattern must be shared and easy to be found (WOODBURY, 2010).

The CLEAR NAMES pattern is mandatory because it is a prerequisite for a model to be useful beyond its creation date. Good names carry the design meaning, the variable content and constraint properties. Names that are not meaningful results in mistakes and mess in the programs. It takes time to think about good names, but it is worth it. The CONTROLLER pattern is helpful to simplify interaction tasks in the main model by creating a separate model whose inputs link to the inputs of the main model. Controllers are independent models that can be easily connected or disconnected. When a property changes in the controller, a change occurs in the main model. Figure 18 shows a Sample of a Controller in which moving a point in the controller (Horizontal line) changes the length of the vertical line. The JIG pattern expresses the structure and form of a model. Jigs resemble Controllers but are more complex and have more links than Controllers. A Jig functions like a more specialized controller, but it is embedded within a host model. Actually, the main model is built directly on top of the jig. A Jig is a simplified version of the main model. As a woodworking jig has the purpose to replicate tasks with accuracy, likewise a Jig pattern in software coding helps locate elements with accuracy and at the same time control some parameters of those elements. The POINT COLLECTION pattern is helpful to locate repeating elements by absolute positions or by their spatial relationship with other elements in the neighborhood. It saves time in modeling and reusing a model in multiple contexts. A collection of point-like objects can be used to define repeating elements (WOODBURY, 2010).

Figure 18 - A Controller pattern sample



Source: Woodbury (2010).

The REPORTER pattern means to retrieve implicit information through functions applied to a model in order to be used in another process or part of the model. It can be used when there is a need to provide data or some aspect of a model to another program, process or part of the model. A Report can be a textual or numeric list, or a geometric part of a model sent to another model, or to new objects. Generally, copying, mirroring, and rotating are ways of reporting a model. A Reporter is recommended to replace tedious and error-prone tasks. In analogy to a relational database, a Reporter pattern is like to extract a table from a database and may demand a complex algorithm. A Report must contain only the information needed. Therefore, it requires judgment to think about the data that the person or model receiving it needs. This pattern typically combines with other patterns as it provides information to other objects. In a way, the Reporter pattern is the opposite of a Controller pattern, because in a Controller, the information flows from source to target and in a Reporter patterns the information flows from target to source. A Reporter can transform data from design into data needed for fabrication. The MAPPING pattern is to use a function within ranges of input and output different than those which the function was created. A domain is a set of input values and range is a set of outputs. In order to simplify the creation of a complex model, Mapping separates where a function is defined from where a function is used. Mapping can also be helpful to make feasible the fabrication of a model by repetitive use of a function in different domain and/or range. The repetitive use of simple functions can simplify a complex design. (WOODBURY, 2010).

3. RESEARCH METHOD

According to Simon (1996), *Design Science* is the science of the artificial[9]. *Design Science* is developed basically under three classical model of scientific inquiry: abduction, deduction, and induction. Prior to 1865, thinkers on logic commonly divided arguments into two subclasses: the class of deductive argumention that resulted in necessary inferences and the class of induction argumentation that resulted in probable inferences. Charles Sanders Peirce added a third type of argumentation, the abductive, which also results in probable inferences. Peirce (2014) clearly defines these three models of scientific inquiry. Abduction is considered a creative process, the only scientific method that allows the introduction of a new idea. Abduction suggests the likely. Deduction starts from laws and theories. The deduction is the proposition of elements that might be used to predict or explain some phenomena. Induction is the generalization of some phenomena to propose a law or theory. Induction is an assertion from what is.

Design Science Research is a research method based on *Design Science.* The reason that led to the choice of the *Design Science Research* as the major method to conduct this research is that it is aimed at the prescription of solutions of problems, seeking to overcome the dichotomy between theory and practice, enabling researchers to find solutions to problems rather than just explain them. Therefore, through it, greater impact can be achieved both on industry and academia. Dresch *et al.* (2015, p.109) state that the output in this method can be five types of artifacts related to each other as shown in Figure 19. A **Construct** is a conceptualization used to describe problems, specify their solutions or to define terms used when describing tasks. A **Model** is a set of statements expressing relationships among constructs or describing how things are. A **Method** is a set of steps required to perform certain tasks. A part of a model can be a step in a method. It is the typical creation of Design-Science based research. **Instantiation** is the operationalization of the first three artifacts. It is a set of rules seeking to demonstrate the feasibility of a construct, a model or a method in a real environment. Finally, **Design proposition** is a theoretical

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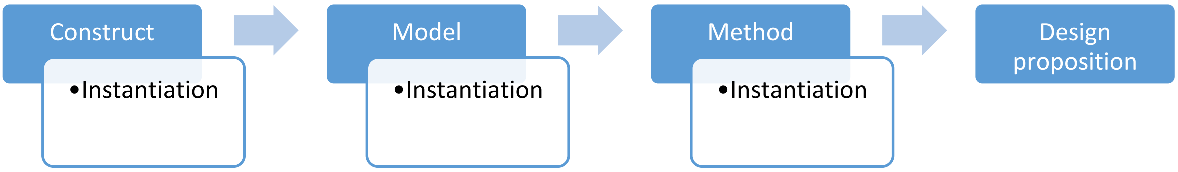
[9] Artificial, according to Simon, (1996) is almost every element in our environment, that shows evidence of human interference. From the temperature, we spend most of our hours that is kept always stable, to the filtered air we breathe. Artificial is something that is man-made, it is certain phenomena that are as they are only because a system is being molded to the environment in which it lives.

contribution; a generalization of a solution to a class of problems.

Figure 19 - Design science research products - artifacts



Source: Adapted from Dresch *et al*. (2015).

The *Design Science Research* method advocated by DRESCH *et al.* (2015) has 12 main steps, summarized in Figure 20 and the output of each step is as follows:

(1) Identification of the problem: The output at the problem identification step is the formalization of the research question;

(2) Problem awareness: The output at the problem awareness is the understanding of the environment of the problem;

(3) Systematic Literature Review (SLR): through an SLR comes to the formalization of all aspects of the problem;

(4) Artifacts' identification: The output at this phase is the existing artifacts, identified through the systematic literature review, and grouped by classes of problems;

(5) Artifacts' proposition: The output at this stage is the formalized artifacts' proposal;

(6) Artifact's design: The output at this step is the definition of techniques and tools for the artifact development and the details of the artifact's requirements;

(7) Artifact's development: The output at this step is the construction heuristics[10],i.e. the artifact in its functional state;

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[10] Heuristic: as an adjective, relates to the process of gaining knowledge or some desired result by intelligent guesswork. The terms seem to have two usages: (1) describing an approach to learning by trying without necessarily having an organized hypothesis or way of proving that the results proved or disproved the hypothesis; (2) Pertaining to the use of the general knowledge gained by experience, sometimes expressed as "using a rule of thumb" As a noun, it is a specific rule-of-thumb or argument derived from experience. (http://whatis.techtarget.com/definition/heuristic)

Construction Heuristics: "*The requirements for the proper functioning of the inner environment of the artifact, according to the outer envirionment. The internal mechanisms and their organization are exposed, considering the desired effects on the natural or outer environment...Construction heuristics generate specific knowledge that can also be used to design new artifacts in the future*." (DRESCH et. al. 2015, pp113)

Contingency Heuristics:"*defines the limits of the artifact, its conditions of use, and the situations in which it will be useful. It is the characterization of the outer environment of the artifact, that is, the context in which the artifact can be used and its performance limits, among other factors. The contingency heuristics can be used to design and build new artifacts*." (DRESCH et. alli, 2015, pp113)

(8) Artifact’s evaluation: The output at this step is the contingency heuristics, i.e., the artifact evaluated, with its limits, conditions, and context of use;

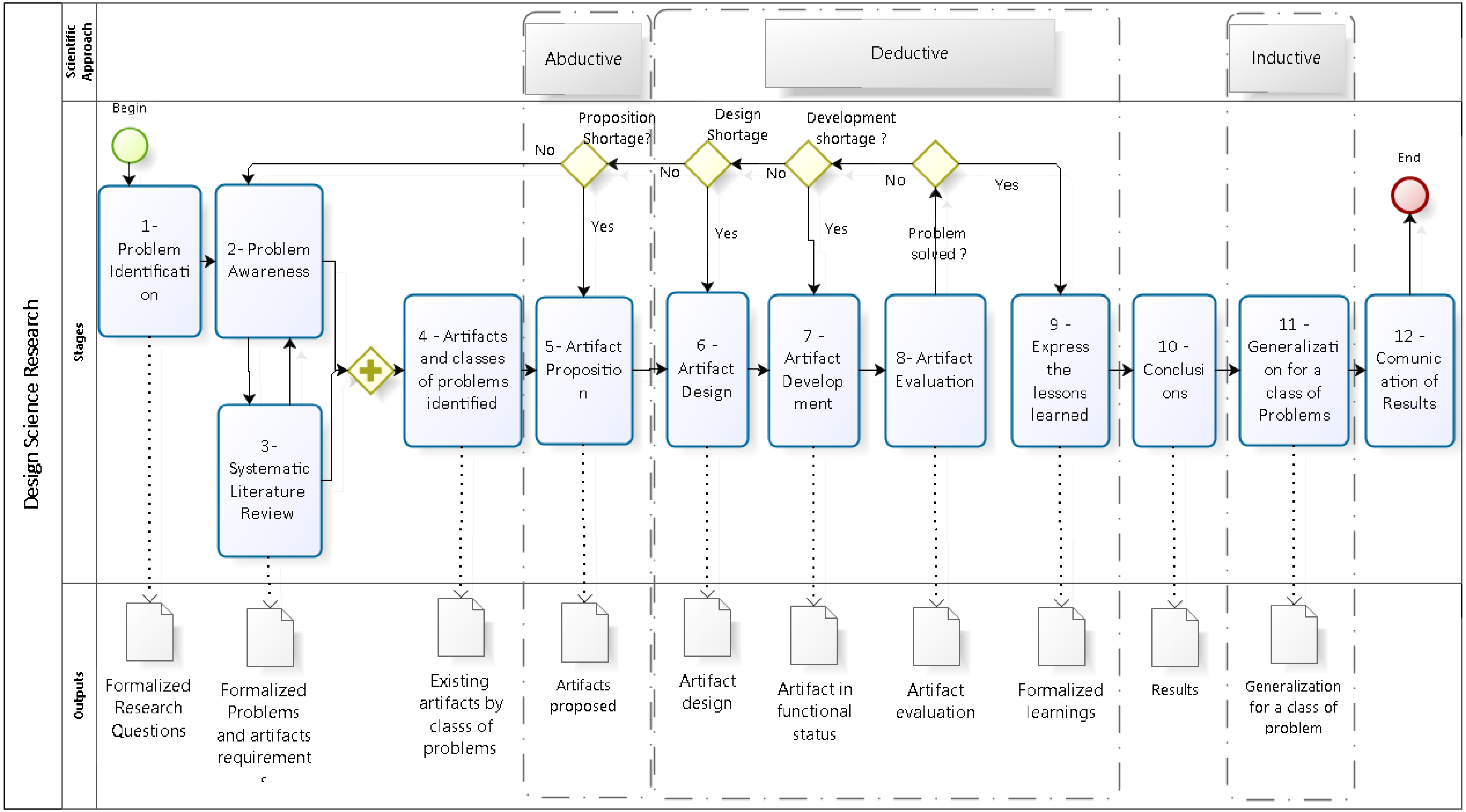
(9) Clarification of learning achieved: The output at this step is the explicit identification of the elements that positively contributed to the generation of theoretical or practical knowledge and the elements that failed.

(10) Conclusion: The output at this step is the limitations of the research and the main decisions made;

(11) Generalization for a class of problems: Through inductive reasoning, the output of this step allows the construction and contingency heuristics generated in a specific situation to be applied to a certain class of problems;

(12) Communication of the results: The output at this step is publications in journals, magazines, and conferences.

Figure 20 - Method for conducting design science research



Source: Adapted from Dresch *et al.* (2015).

Within the proposed delineation of the method shown in Figure 20, the second and third steps can be cyclical, i.e., together they aim to define the problem and support the identification of existing artifacts created in the academia. For this research, the second step, **Problem awareness**, was conducted through a case study. The third step, **Systematic Literature Review** was a critical step, because together with the problem awareness subsidized the identification of existing artifacts and classes of problems, which is the fourth step of the process, serving as inspiration and basis for the next step's ideation. The outcomes at the fifth step, **Proposition of artifacts**, are introductions of new ideas, or suggestions of the likely. This is essentially a creative process; therefore, according to the classical model of scientific inquiry, it is abductive reasoning, which is the only scientific method that allows the introduction of a new idea. The sixth, seventh, eighth and ninth steps, namely, design, development and evaluation of the artifact, and the expression of the lessons learned, were conducted cyclically in this research through an action research performed in two cycles in the context of a small fabricator of engineered-to-order components, specialized in design and production of custom kitchens and other furniture cabinetry. In each cycle, After the artifact's evaluation, questions were asked, in order to identify whether the artifact developed was able to solve the problem identified in the Problem awareness stage. If the answers indicated that the problem was not solved, further questions were formulated in order to identify if the cause was an artifact development issue, or if it was an artifact's design issue. In case of an artifact development issue, the seventh step was to be performed again, but if it was an artifact's design issue, then the artifact design would be revised. That is, the answers to each question would determine the actions to be performed in the second cycle. The outcomes from the cyclic process were four types of artifacts: some constructs, a model, a method derived from the model, and an instantiation to validate the method. This process was deductive reasoning according to the classical model of scientific inquiry.

3.1. Problem Identification

In this study, the problem identification was presented in the chapters of INTRODUCTION and CONCEPTUAL BACKGROUND. It came as an effort to find a solution to typical problems faced by engineered-to-order components fabricators such as (1) Most of their labor effort is spent producing and updating documents, increasing the indirect costs; (2) Design and production have high rates of inaccuracies and inconsistencies that are discovered only in later phases of the Project; (3) The same information is registered into computers several times, each time for a distinct use; (4) Rework is routine and Project lifecycles are long; (5) Low productivity at the process of detailed design in the context of digital manufacturing of custom products;(6) Fabricators find themselves committing to projects with lead times shorter than the time required to fabrication; (7) Too much efforts required to produce shop drawings. Those problems lead to the following research questions: Which are the artifacts if they exist, developed by the scientific academy aiming to solve those problems? Which are the software and hardware used to develop those artifacts? How to incorporate BIM into an engineered-to-order component fabricator and achieve mass customization?

3.2. Problem Awareness

The case study method was chosen at this stage of the investigation because, according to Gil (2010), it is a suitable method for describing causal variables of a phenomenon in its environment. The study provided an overview of the problems identified in the previous section and identified factors that influence or are influenced by those problems. The problem awareness related to this research is detailed in the fourth chapter and the subject studied is a typical engineered-to-order fabricator of woodworking building components, that has manufactured kitchens and other customized cabinetry using digital fabrication for over two decades. In this research, it was called Company A.

Clients and users are increasingly demanding customized products, but the problems that engineered-to-order components fabricators have faced, cause the design and production costs to be high. This case study aims to identify these problems. Two main reasons pointed to Company A as the organization for the case study. This company has offered for nearly 30 years, customized kitchens and other cabinetry components through a digital manufacturing process. The researcher has a thorough knowledge of the business organization, administration, design, and production processes. Concerning the data collection, the research participants interviewed and observed in this case study are key people who know the company's processes deeply and they have decision-making power. As for the strategy for data collection, the information was collected in 2016, a period in which the researcher played an active role in the process of design and production in the company.

As stated by Gil (2010), the protocol is the document that deals with all the important decisions that were and should be made throughout the case study process. Brereton, Kitchenham, and Budgen (2008) add that one of the most significant benefits of the protocol is to specify the research questions, how they would be answered and to ensure that the data collected, and the analysis procedures can reliably respond to the case study questions. The protocol for this case study is presented in Table 6 and besides explaining the procedures to be adopted in the data collection, the protocol helps the decision-making throughout the research.

The delineation of this case study followed the suggested by Gil (2010) and is summarized as follows:(1) The case study begins with the formulation of a problem. In this research, the question is: What are the typical problems faced by engineered-to-order components fabricators? (2) This study refers to a typical case carried out in a single organization, and the purpose of the study is to know its problems in depth without concern regarding the development of a theory. (3) An engineered-to-order fabricator of custom kitchens was selected. The undertaking is a company that according to the classification of Lampel and Mintzberg (1996), apply a manufacturing strategy of Pure Customization and is aiming at achieving mass customization; (4) In the literature, there is no fixed model for the case study protocol elaboration. Therefore, this study adopted the structure suggested by Brereton, Kitchenham and Budgen (2008) described in the Table 6 (5) Data collection: Informal Interviews with the Chief Executive Officer - CEO, Design manager, Engineer Manager and Production Manager; Participant observation with the researcher playing an active role in the researched company; Access to documents, such as organization's database, design and engineering specifications and drawings, client's profile, and job descriptions; (6) Data analysis occurred simultaneously with data collection, when. relevant concepts found in documents, interviews, and observations were coded and patterns identified from data were categorized for the purpose of grouping them and for the elaboration of discursive text; (7) Validation of the study was established by the selection of the appropriate source of information and with data collection through repeated contacts with the sources:

Table 6 - Case study protocol

Objective	Clients are increasingly demanding customized products, but the problems that engineered-to-order components fabricators have faced, cause the design and production costs to be high. This case study aims to identify these problems.
Data Collection strategy	Informal Interviews. Participant observation Design, engineering and administrative document reviews
Data analysis strategy	The colletected data were coded and grouped by: Project Acquisition, Detailed Design Production
Plan validity	The data were collected in 2016 and are related to a period of about six years. Careful selection of reliable sources of informations
Research Questions	
Project Acquisition:	How efficient is the process of producing and updating Project Acquisition documents? How accurate and consistent are the documents generated at Project Acquisition? How are informations registered throughout the design and engineering process? Are they registered into computers in the company's servers? Are they registered in the "Clouds", through the web? Or printed reports are generated?
Detailed Design	How efficient is the process of producing and updating Detailed Design documents? How accurate and consistent are the documents generated at Detailed Design? How much effort is required to produce shop drawings? Does the library of customizable components suit the needs of engineers?
Production	Where is the weakest point in the manufacturing process in terms of rework and meeting the schedule? Is it in the Design, in the engineering or in the production? Where rework is more frequent? Is the commitment to project's lead times compatible with the time required to fabrication? What are the problems related to the fabrication of components that are subcontracted?

Source: Adapted from Brereton, Kitchenham and Budgen (2008).

Data collection and data analysis were performed simultaneously over a period of one year when the researcher played a strategic role in the integration of information and communication among design, engineering and production specialists. Therefore, the researcher is qualified to perform the role of participant-observer in this case study. Data analysis was performed through aggregation of data by categories and by direct interpretation. Data validation was performed through triangulation [11] of data collected from interviews, observation, and documents. Regarding the study limitations, the research is more concerned with the aspects of processes and procedures and less with human resources aspects. The protocol summarized in Table 6 grouped the research questions according to the macro processes in the cabinetry manufacturing strategy at the studied company.

3.3. Sistematic Literature Review

According to Kitchenham (2004), a Systematic Literature Review (SLR) demands significantly more efforts than the classic literature review, but its main benefit is to provide information about the effects of a phenomenon. The SLR offers evidence that the phenomenon is robust and transferable. According to Dresch *et al.* (2015), the SLR is an essential step for research conducted under a *Design Science Research (DSR).* Prior to undertaking an SLR, the researcher defines a protocol. In the opinion of Kitchenham (2004), the components of a protocol include the reason for the survey, the search questions, the search strategy, the study selection criteria, the study quality assessment, data extraction strategy, and data synthesis.

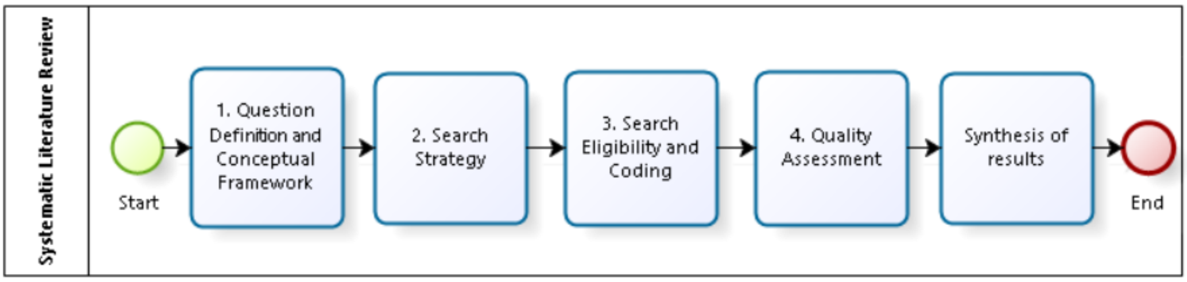
Kitchenham (2004) asserts that an SLR can benefit from a preliminary search that helps to set up the SLR and to assess the volume of potentially relevant studies. The researcher in this investigation decided to conduct an exploratory search before the SLR. The goal of this preliminary search was to define reliable parameters for the protocol elaboration in the SLR. In this preliminary exploratory search, 329 studies where found in the following database sources: ASTM-American Society for Testing and Materials, Compendex Ei- Engineering Village, JCR-Journal Citation reports, Proquest, Web of Science, Emerald, Scopus, ASCE Library-American Society of Civil Engineers, Portal de Periodicos Capes, Scielo, BDTD-*Biblioteca Digital Brasileira de Teses e Dissertações*. The keyword used were: Mass

[11] Triangulation: Cross-analysis. A fact or object is studied from a variaty of points. (Barnet and Thomas, 2009)

customization, BIM and Digital fabrication. After the exclusion of repeated studies, the researcher performed a reading of titles, keywords, and abstracts without identifying the authors and resource centers aiming to reduce bias. Then significant search terms, database sources, research population, and languages of the studies were identified and set as parameters to be used later in the elaboration of the protocol of the SLR.

There are various methods for conducting a Systematic Literature Review, and this investigation adopted the method suggested by Dresch *et al.* (2015, pp.132) that is summarized in Figure 21, as follows: (1) The Question definition and the conceptual framework is the first step and explains the scope of the review - that is, the variety of studies searched, the type of questions, whether they are open questions designed to cover a topic more broadly, or if they are closed questions that lead the review with a more specific approach; (2) The search strategy step, is the definition of which scientific bibliographic databases are the source for the search, as well as the types, languages, and keywords of the studies to be searched. At this stage, the Systematic Literature Review protocol was defined, showing that the topics were fully interconnected in order to allow the researcher to answer the review questions. For example, the search terms for the SLR were carefully defined in order to minimize deviations and distortions; (3) Search, eligibility and coding: At this step, the search strategy was operationalized, i.e., primary studies were searched, selected and coded for further evaluation, synthesis and results. This stage was thoroughly documented in order to ensure that the Systematic Literature Review could be followed or tracked down; (4) Quality assessment: The reliability of the results from the Systematic Literature Review, and its associated usefulness to stakeholders rely on the studies quality criteria that defined each study relevance to the Systematic Literature Review. The quality criteria were defined and tabulated at this stage; (5) Synthesis of results is the interconnected combination of the results in order to generate new knowledge that did not exist in the original primary studies. Data Synthesis activities implied grouping and summarising the included primary studies and are specified in the protocol. The synthesis was qualitative and is presented in a tabular format. The data extracted from the selected studies and documented in forms were summarized through a technique called triangulation.

Figure 21 -Systematic Literature Review Method



Source: Adapted from Dresch *et al.* (2015).

3.3.1. Question Definition and the Conceptual Framework

The conceptual framework is like a reference point for conducting the research. It provides the background in order to appropriately define the research activities. It is useful because a Systematic Literature Review can cover a wide scope or may focus on a specific approach, depending on the type of questions. The Systematic Literature Review can have a wide variety of questions, presenting both quantitative and qualitative characteristics. In the first case, the researcher tries to understand which artifacts have been used successfully for the solution of a given problem, but without a statistical approach. In the second case, he is trying to explore the context in which each study was carried out and to understand under which circumstances an artifact has better conditions to generate the expected results. Therefore, regarding the extension of the research, the saturation strategy is adopted, i.e., the number of primary studies selected are the necessary and sufficient to give a logical and reasonable answer to the review question.

In this Systematic Literature Review, existing artifacts are identified, then classified by the corresponding benefits, the technology that supports each artifact and their application. Finally, research centers and research methods are categorized. The research questions for the Systematic Literature Review are as follows:

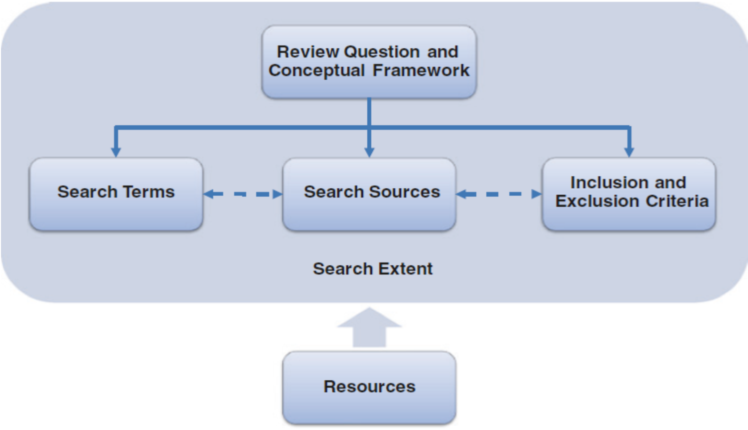
- Which are the existing artifacts developed for the AEC industry, in the context of BIM, Digital fabrication and Mass Customization? Which are the stakeholders for each artifact?
- Which are the artifacts benefits in terms of productivity, customization, interoperability and life cycle integration? How are those benefits categorized by stakeholder and by artifact type?

- Which are the artifacts supporting technology (software/hardware)? How can this tool be classified by benefits and by context?
- Which is the artifacts application in terms of construction components, interior design, and architectural elements? Each artifact application is in the interest of which stakeholders?
- Which are the research centers involved in the development of the identified artifacts? What are the research methods used?

3.3.2. Search Strategy

According to Dresch *et al.* (2015), a Systematic Literature Review manages a large amount of information, therefore requires a search strategy that aims to answer questions such as: What to search for? Where to search? How to minimize deviations and distortions? Which studies to consider? What are the criteria for inclusion and exclusion of studies in the review? What is the extent of the search? What are the available resources? The search terms to be used are strongly associated with the Review Question and should be able to identify the problem and its context. The topics related to the search strategy are fully interconnected as illustrated in Figure 22. After the definition of review questions and the conceptual framework, the search terms, the search sources, the inclusion and exclusion criteria are defined almost simultaneously aiming to define the search extent necessary to answer the review questions. The search terms, search sources, inclusion criteria, and exclusion criteria were defined based on the exploratory search conducted before the SLR. This previous and careful definition of the search terms was conducted in order to minimize deviations and distortions. All these parameters are part of the SLR protocol presented in Table 7.

Figure 22 - Search strategy



Source: Dresch *et al.* (2015).

According to the opinion of Kitchenham (2004) and Dresch *et al.* (2015), the SLR protocol presented in Table 7 holds the following parameters: The **objective** of the Systematic Literature Review is to support the research's problem awareness phase by consulting the existing knowledge generated from science. **Interventions** are the technologies that address issues related to the research questions, and a comparison between classes of problems that each technology addresses. The **Population** of studies that are relevant to the investigation. A population was defined in order to hedge the number of feasible primary studies. **Outcomes**: are the important factors that were used to compare the interventions. The **research questions** that the Systematic Literature Review is intended to answer, are related to the objective, intervention, population, and outcomes. **Control group** of studies are outcomes from a prospective group of studies collected prior to the Systematic Literature Review. They are compared with the studies selected in the Systematic Literature Review. **Who might be interested** in the research? To whom the Systematic Literature Review is meaningful? The s**earch strategy** is the factor that allows the Systematic Literature Review to be sufficiently documented and performed in a transparent, reliable and replicable way. It contains the Search sources, Studies types, Search languages, Search terms, Inclusion criteria and Exclusion criteria. The studies excluded and the reason for the exclusion was presented in the appendices. **Data extraction** includes parameters that were extracted from the selected studies and tabulated, which are: artifact's description, artifact's type, results that they provoke, the kind of problem that those artifact solve, the artifacts constructive and contingency heuristics, the context of the study, its benefits, stakeholders, tools used in the development of the artifact(software and hardware), artifact's application, research center, research method, relevance to the review focus and study evaluation. **Summary of the results** specifies the synthesis technique adopted, that is, *triangulation*, which according to Barnet-Page and Thomas (2009) unpacks the relationship between intervention, outcomes, and population in order to answer this typical question: "What type of intervention causes what type of outcomes for what type of population under what type of conditions? In this investigation, the question is "What type of artifacts causes what type of results for what type of problem under what type of conditions?

Search strategy encompasses the following **Search sources**, i.e., the scientific databases where studies were selected from Emerald, Scopus, Web of Science, American Society of Civil Engineers (ASCE) and *Biblioteca Digital Brasileira de Teses e Dissertações* (BDTD). The search strategy also holds the **Studies types**, which are the ones, selected mainly from scientific papers in indexed periodicals and from Brazilian Master and Doctoral thesis. **Languages** for the selected studies should be English for being internationally accepted in the scientific academia or Portuguese in order to contemplate studies written by Brazilian researchers. **Search terms** were created with the following keywords: BIM, Building Information Modeling, Mass Customization, Digital Fabrication, Design to Fabrication, Manufactur*, Construction, Architecture, and Fabrication. **Inclusion criteria** were applied during the search process, and the **exclusion criteria** were applied in the eligibility and coding phase

Regarding to the first inclusion criteria, the previously conducted exploratory search allowed a precise definition of the period of search, as publication date of the studies was defined as from January 1997, which is the date of the oldest publication found on the mass customization subject, whose title is: *The four faces of mass customization,* and was downloaded from https://hbr.org. The second inclusion criteria prescribed that studies should contain the search terms in titles, abstracts or keywords. Finally, the third inclusion criteria determined that studies should be written in English or Portuguese. The eight exclusion criteria applied in the eligibility and coding phase are: (1) Repeated study; (2) study with full text not available; (3) Study not written in English or Portuguese; (4) study whose method is not explicitly proposed; (5) Study that does not follows the proposed method; (6) Study whose results do not rely entirely on facts and data; (7) Study that only touches the target subject of the Systematic Literature Review; (8) Study that was conducted in a different context to the one defined for the review. The exclusion criteria 4 to 8 are the studies evaluated as low by the evaluation criteria presented in Table 9. Regarding the exclusion criteria in relation to the publication language, it was applied on studies that were not entirely written in English or Portuguese were excluded.

Table 7 - Systematic Literature review protocol (continues)

Objective (Target)	Identify and qualify existing artifacts in automated design and fabrication mediated by BIM for mass customization. Characterize research associated to develop these artifacts
Intervention (Context/focus)	Artifacts in terms of Design Science Research (constructs, models, methods, instantiation, design proposition) related to BIM, Digital Fabrication, Mass Customization and Design to Fabrication in the Architecture, Engineering and Construction industry
Population	International studies published in English journals and Thesis submitted in Brazil.
Outcomes	Benefits, results, context, application and problems addressed by the artifact. The outcomes are factors that allow to answer the following question: What type of artifacts cause what type of results for what type of problems under which heuristics?
Research Questions	1. Which are the existing artifacts in terms of Design Science Research (constructs, models, methods, instantiation, design proposition)? And in which context (BIM, Digital Fabrication, Mass Customization and Design to Fabrication in the Architecture, Engineering and Construction industry)? Which are the stakeholders?
	2. Which are the artifacts benefits in terms of productivity, customization, interoperability, life cycle integration? Which are the benefits by stakeholder? Which are the benefits by artifact type?
	3. Which are the artifacts supporting tools (software and hardware)? What are the tools by benefit? Which are the tools by context?
	4. Which are the artifacts application (construction components, interior design, architectural elements) and to the interest of which stakeholders?
	5. Which are the research centers involved in the development of the identified artifacts? What are the research methods used?
Control	LINNER, T., BOCK, T., (2012),"Evolution of large-scale industrialisation and service innovation in Japanese prefabrication industry", Construction Innovation, Vol. 12 Iss 2 pp. 156 - 178
	KHALILI-ARAGHI, S., KOLAREVIC, B., Development of a framework for dimensional customization system: A novel method for customer participation, s.l, Journal of Building Engineering, 2016
	FARR, E., R., P., PIROOZFAR, P., A., E., ROBINSON, D., **BIM as a generic configurator for facilitation of customisation in the AEC industry**, s.l, Automation in Construction, 2014
	LEON, Alexander Pena et al., **A Flexible Automated Digital Design For Production Workflow**, , Australia,Proceedings Of The 18th International Conference On Computer-Aided Architectural Design Research In Asia (CAADRIA 2013), 2013, Páginas:643-652
	LUTH, Gregory P., **VDC and the Engineering Continuum**, , USA,Journal of Construction Engineering and Management,2011, Vol. 137, No. 10, pp. 906-915

Table 8 - Systematic Literature review protocol (conclusion)

Control		GATTAS, J. M. ; YOU, Z.,**Design and digital fabrication of folded sandwich structures**,,Australia,Automation in Construction,2016
		POIRIER, E.; STAUB-FRENCH, S.; FORGUES, D., **Embedded contexts of innovation: BIM adoption and implementation for a specialty contracting SME**, , , Construction Innovation, Vol.15 Iss 1 pp. 42-65,2015
		NEWMAN, S.T., et.al., Strategic advantages of interoperability for global manufacturing using CNC technology, , Robotics and Computer-Integrated Manufacturing, 2014
Who might be interested in the research		BIM researchers interested in engineered-to-order digital fabrication of building components.
Search Strategy	Search Sources	Emerald Insight - Advanced Search (www.emeraldinsight.com); Scopus (https://www.scopus.com); Web of Science (https://apps.webofknowledge.com); American Society of Civil Engineers (ASCE - http://ascelibrary.org). ; BDTD – Biblioteca Digital Brasileira de Teses e Dissertações - http://bdtd.ibict.br/vufind/;
	Studies type	Scientific papers in indexed periodicals and peer reviewed / Brazilian dissertations and Theses
	Search Languages	English (language internationally accepted) / Portuguese (to contemplate existing papers by Brazilian researchers)
	Search terms	BIM AND Fabrication / Building Information Modeling AND Fabrication / BIM AND Mass customization / Building Information Modeling AND Mass customization / BIM AND Digital fabrication / Building Information Modeling AND Digital fabrication / Design to Fabrication AND Architecture / Design to Fabrication AND Manufactur* / Design to Fabrication AND Construction
	Inclusion Criteria	1. Articles, dissertations and thesis since 1997 (publication date of: The four faces of mass customization (available at https://hbr.org/1997/01/the-four-faces-of-mass-customization, downloaded 2016/Oct/09). Articles must have been published in journals or conference proceedings with peer review. Dissertations and theses must have been approved in examination board
		2. Studies that contain the research terms in: Title, abstract or keywords.
		3. Abstract written in English.
	Exclusion Criteria	1. Repeated
		2. Full text not available.
		3. Study not written in one of the research specified languages (English or Portuguese).
		4. Study whose method is not explicitly proposed (Study evaluated as LOW at the Criteria For Evaluation Of The Quality Of The Primary Studies)
		5. Study does not follows the proposed method (Study evaluated as LOW at the Criteria For Evaluation Of The Quality Of The Primary Studies)
		6. The results do not rely entirely on facts and data (Study evaluated as LOW at the Criteria For Evaluation Of The Quality Of The Primary Studies)
		7. The study only touches the target subject of the Systematic review. (Low Relevance to the review question)
		8. The study was conducted in a different context to the one defined for the review. (low Relevance to the review focus)
Data extraction		Artifact's description, artifact's type, Which are the results that they provoke? For what kind of problem? What are the constructive and contingencial heuristics? Context of the study; benefits, stakeholders, tools used in the development of the artifact (software and hardware); artifact's application; research center, research method, relevance to the question relevance to the review focus and study evaluation.
Summary of results		What type of artifact causes what type of result for what type of problem under which heuristics?

Source: The author.

Table 9 - Criteria for Evaluation of the Quality of the Primary Studies

Evaluation	Quality of the study performance	Relevance to the review question	Relevance to the review focus
High	The proposed method meets the standards required for the study AND the study strictly follows the proposed method AND the results rely on facts and data.	The study addresses precisely the target subject of the Systematic review.	The study was conducted in an identical context to the one defined for the review.
Medium	The proposed method has weaknesses regarding to the standards required for the study OR the study does not strictly follow the proposed method OR the results do not rely entirely on facts and data.	The study addresses partially the target subject of the Systematic review.	The study was conducted in a context that resembles the one defined for the review.
Low	The proposed method does not meet the standards required for the study (Exclusion criteria 4) OR the study does not follow the proposed method (Exclusion criteria 5) OR the results do not rely entirely on facts and data. (Exclusion criteria 6)	The study only touches the target subject of the Systematic review. (Exclusion criteria 7)	The study was conducted in a different context to the one defined for the review. (Exclusion criteria 8)

Source: Dresch *et al.* (2015).

3.3.3. Search, Eligibility and Coding

The search was carried out simultaneously with its documentation, i.e., any action that occurs differently from the planned strategy was noted. Strings were constructed with keywords defined in the protocol and submitted to the following search engines: Emerald Insight, SCOPUS, Web of Science, American Society of Civil Engineers - ASCE library and Biblioteca Digital Brasileira de Teses e Dissertações. The keywords defined in the protocol were defined in an exploratory research conducted prior to the Systematic Literature Review (SLR) and they are: “BIM”, “Building Information Modeling”, “Fabrication”, “Mass Customization”, “Digital

Fabrication”, “Design to Fabrication”, “Architecture”, “Manufactur*”, “Construction”.

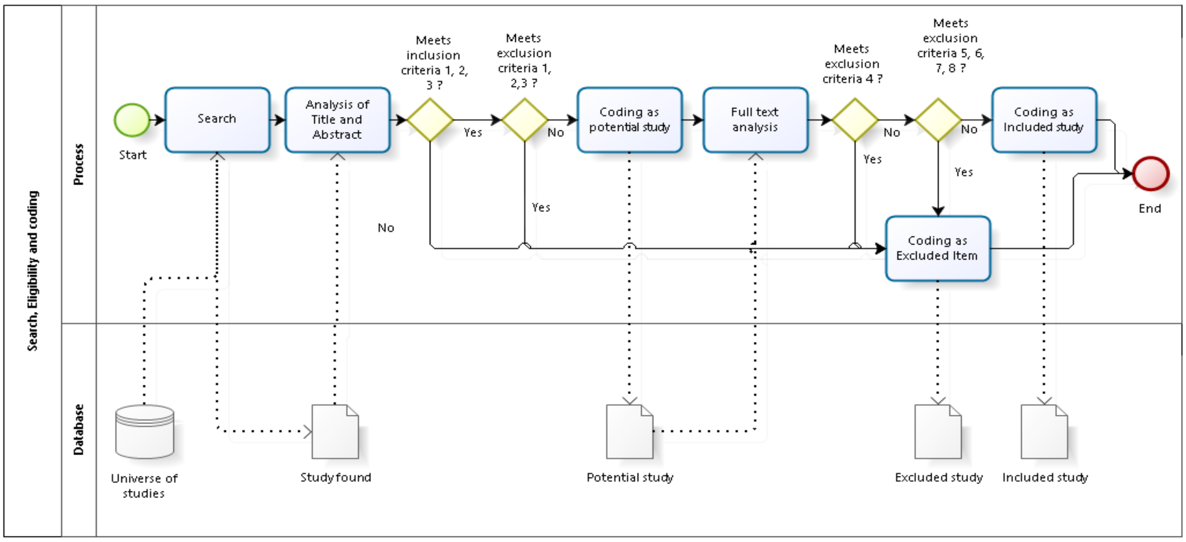
According to Kitchenham (2004) and Dresch *et al.* (2015), search, eligibility, and coding are stages associated with conducting the SLR. Search is the selection of primary studies, a process governed by the inclusion and exclusion criteria specified when the protocol was defined. During this process, data extraction forms are prepared. Eligibility is to determine the relevance of each study to the review. Coding is the process of substantiating the search sufficiently to allow other researchers to deeply assess the search. In the coding process, included studies are categorized and characterized and the excluded studies are given the reason for their exclusion. The search process in this SLR is documented at the data extraction forms presented from appendix B to Appendix F. They were prepared during the selection of primary studies and updated during the eligibility and coding stages. In the coding process of the included studies in this investigation, concepts and artifacts were identified and codes were created through qualitative analysis of each study.

Search, eligibility, and coding are performed sequentially. The sequence suggested by Dresch *et al.* (2015) is presented in the general process map shown in Figure 23. It shows that initially the search terms defined in the protocol are applied to the source population also defined in the protocol. The first three inclusion criteria defined for this research were applied at the searching process, - that is, the first inclusion criteria mean the selection of articles published after 1997 in journals or conference proceedings and thesis approved in examination boards. The second inclusion criteria stand for the selection of studies that contain the search terms in the title, abstract or keywords, and the third inclusion criteria imply the selection of studies written in English.

After this initial inclusion and exclusion performed through the analysis of titles, keywords, and abstracts, the remaining studies were coded as a potential study. To those studies, a full-text reading in which the researcher was seeking a deep understanding of the study was performed, and the remaining exclusion criteria were applied. Based on the fourth exclusion criteria, studies whose method is not explicitly identified were excluded and coded for possible further analysis. To the remaining studies, the exclusion criteria number five, six, seven and eight were applied, and they are: studies that do not follow the proposed method, studies whose results do not rely entirely on facts and data, studies that just mentioned the target subject of the systematic review and studies conducted in a different context to the one defined to the review. The remaining studies after this screening were coded and categorized for a subsequent quality assessment to determine the relevance of the study to the review question and to the review focus. Every excluded study was coded and saved for possible future analysis. At the end of this process, the remaining studies were selected and coded. To those, the quality assessment to determine the relevance of the study to the review question and the review focus was applied.

This process was recorded in a document named *Form for Conducting the Systematic Review*. The form contains the following information: Name of the electronic database source, name of the journal or title of the conference procedure, years searched, search string, URL for the search and list of reference of the studies found. For each combination of search engine plus search string, one form was created. Each form has not only the search history but also the exclusion criteria for each excluded study and they are depicted in the appendices. Finally, in the quality assessment, in case a study was considered not eligible for the synthesis of results, the exclusion criteria of the study were registered in that table. This process allows the SLR to be traced back.

Figure 23 - Summary of the Search, Eligibility and Coding process



Source: Adapted from Dresch *et al.* (2015).

3.3.4. Quality Assessment

According to Kitchenham (2004) and Dresch *et al.* (2015), quality assessment is a multistage process associated with conducting the SLR. The confidence of the SLR conclusions is as higher as the reliability of each selected study. Once the potentially relevant studies have been selected, they need to be analyzed for their actual relevance assessment. This is performed through the study selection criteria. In order to reduce chances of bias, and to guide the interpretation of findings, the selection criteria were also defined during the protocol definition stage. Quality assessment is related to minimizing the chances of selecting studies that produce no reliable results and maximizing the chances of selecting studies whose results are applicable outside of the study. The higher the quality of a systematic review the greater the confidence in their conclusions. The relevance of the review is evaluated considering not only its process but also the quality of the studies selected. An appropriate search strategy, e.g., inclusion and exclusion criteria clearly defined, affects the review quality (DRESCH *et al.,* 2015). The quality assessment of the selected studies in this SLR was determined by the Criteria for Evaluation of the Quality of the Primary Studies depicted in Table 9 and they are embedded in the exclusion criteria defined in the Protocol. The exclusion criteria 4, 5 and 6 characterize the quality of the study by itself, that is, if the proposed method is not appropriate for the study, or the study does not follow the proposed method or the results do not rely on facts and data, it is classified as low quality. The exclusion criteria 7 tests the relevance of the study to the review question, and the exclusion criteria 8 verifies whether the study meets the condition for relevance to the review focus.

After performing evaluations for each criterion, the scores were consolidated to provide a general score to the study. The consolidation scale is presented in Table 10. Studies evaluated as low quality were excluded. Studies classified as low relevance to the review focus were evaluated as low quality for the research even in the cases that the quality of the study by itself was classified as high or the relevance to the review question was classified as high. This strictness is due to the effort on reducing the chances of bias.

3.3.5. Synthesis of results

The synthesis of results was realized in three steps: The first one is the analysis and organization of available data. The second one is the identification of patterns between them, and, the third one is data integration. After the quality assessment referred to in the previous step, a data extraction form was filled for each study considered relevant to the investigation. That form contains the following informations: The artifact's description, the artifact's type, the results that the artifacts cause, the kind of problem the study deals with, the artifacts's constructive and contingency heuristics, that is, how the artifact functions internally, its limits, conditions and context of use, the context of each study, that is, BIM, Mass Customization, Digital Fabrication or Design to Fabrication. The forms also contain the benefits of each study in terms of productivity, customization, interoperability or lifecycle integration, the stakeholders that might be interested in the study's subject, the tools used in the development of the artifact, both software and hardware, the artifact's application, the research center, the research method, the study's relevance to the review question, the study's relevance to the review focus and the overall study evaluation. The complete set of the forms containing information on all selected studies is presented in the appendices. After the analysis and organization of available data, the studies were grouped into categories for the identification of patterns between them and the data integration. Then, existing artifacts and classes of problems were identified.

Table 10 - Criteria for Assessment consolidation

Quality of the study performance	Relevance to the review question	Relevance to the review focus	Study Evaluation
High	High	High	High
High	High	Medium	Medium
High	Medium	Medium	Medium
Medium	Medium	Medium	Medium
High	High	Low	Low
High	Medium	Low	Low
Medium	Medium	Low	Low
Medium	Low	Low	Low
Low	Low	Low	Low

Source: Dresch *et al.* (2015).

3.4. Identification of Existing Artifacts and Classes of Problems

The main objective of this step was to answer the following question: What type of artifact causes what type of result for what type of problem under which conditions? This question was answered through a synthesis technique named "triangulation", that according to Dresch et al, (2015) is the best synthesis method suited to SLR. The Synthesis begins with the data extracted from the selected studies being tabulated according to the template proposed by Dresch et al, (2015) exemplified in Table 11, that allows the identification of patterns such as, artifact A2 is a robust solution to the problem P1 because it shows positive results under different conditions, but artifact A1 is a weak solution to problem P2 because it shows different results when using different conditions.

The synthesis matrix exemplified in Table 12 was helpful to aggregate the problems into classes. The synthesis began with data extracted from the selected studies being tabulated containing the following information: Reference, problem, artifact, condition, and result. Patterns were identified in order to aggregate the problems into classes of problems. The complete set containing information on all selected studies are presented in the appendices

Table 11 - Proposed data organization for the synthesis

Primary study	Problem	Artifact	Condition	Results
1	P1	A3	C1	negative
2	P2	A1	C4	positive
3	P1	A2	C2	positive
4	P3	A1	C4	positive
5	P1	A2	C3	positive
6	P2	A1	C3	negative

Source: Dresch *et al.* (2015).

Table 12 - Proposed data organization for the synthesis

<table>
<tr><th>Primary study</th><th>Class of problem</th><th>Problem</th><th>Artifact</th><th>Condition</th><th>Results</th></tr>
<tr><td>3</td><td rowspan="6">CP1</td><td rowspan="3">P1</td><td rowspan="2">A2</td><td>C2</td><td>positive</td></tr>
<tr><td>5</td><td>C3</td><td>positive</td></tr>
<tr><td>1</td><td>A3</td><td>C1</td><td>negative</td></tr>
<tr><td>2</td><td rowspan="2">P2</td><td rowspan="2">A1</td><td>C4</td><td>positive</td></tr>
<tr><td>6</td><td>C3</td><td>negative</td></tr>
<tr><td>4</td><td>P3</td><td>A1</td><td>C4</td><td>positive</td></tr>
</table>

Source: Dresch *et al.* (2015).

3.5. Proposition of Artifacts

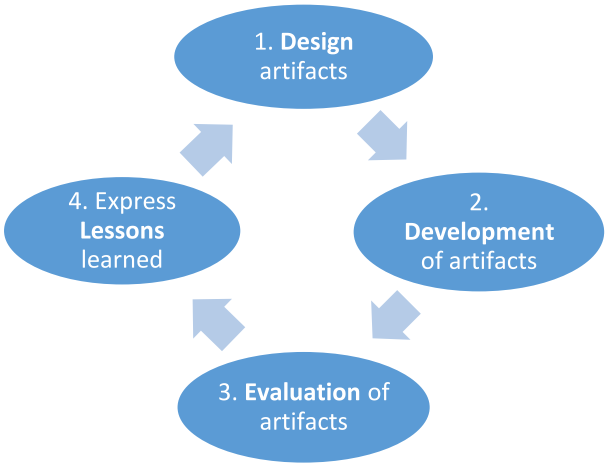
In the previous step, the solutions of the investigation's problems begun to be delineated. By the identification of existing artifacts and classes of problems, the researcher was able to identify artifacts that could be used to solve the investigation's problems and be adapted to the reality studied. In addition, the researcher proposed the creation of new artifacts. The artifact proposition was essentially a creative task. Therefore, the scientific approach in this phase was abductive reasoning, where the researcher used his previous knowledge in order to suggest robust solutions to the problem (DRESCH *et al.,* 2015).

3.6. Artifacts's Design, Development, Evaluation and Expression of Lessons Learned

According to Dresch *et al.* (2015), the sixth, seventh, eighth and ninth steps in a *Design Science Research* are respectively the Artifact's design, development, evaluation and the expression of the lessons learned**.** In this investigation's *Design Science Research,* those steps were performed through action research, as represented in Figure 24. Action research is a systematic way for reflection, thought, discussion, decision and action about what goes on in a specified environment and how to get data from it and develop interventions that help to improve that environment. Gil (2010) defines it as a type of empirical research conceived and carried out in close relation with an action aiming to solve a collective problem. The researcher and participants engage in a cooperative and participatory manner through a cyclical process.

According to Berisha and Pula (2015), it is difficult to find two institutions or countries who classify small and medium enterprises by the same criteria. Berisha and Pula presented the European Union and the World Bank criteria as shown on Table 13. Both, the European Union and the World Bank use the criteria of Number of employees as a quantitative indicator, but they use different standards as qualitative indicators.

Figure 24 - Action research for design, development, evaluation and express lessons learned



Source: The author.

Table 13 - Definition of Small and Medium Enterprises

European Union Standards		
	Number of Employees	Annual turnover or Annual Balance Sheet total
Medium	<250	<= €50 million
Small	<50	<= €10 million
Micro	<10	<= €2 million
World Bank Standards		
	Number of Employees	Total Assets or Total annual sales
Medium	<=300; > 50	>$3.000.000; <=$15.000.000
Small	<=50; >10	>$100.000; <=$3.000.000
Micro	<10	<=$100.000;

Source: Adapted from Berisha and Pula (2015).

This research comprised two cycles whose protocol is summarized in Table 14 and was accomplished in a cooperative and participatory manner with the custom kitchens and cabinetry manufacturer, which was selected for the case study. The researcher's knowledge of the company's operation allowed him to be more participative and interpretative. The studied company has a tradition in offering customers the most advanced technological options available in the market. One of the objectives of this investigation was to propose artifacts for the solution of problems of “*Small and Medium Enterprise*” (SME) and the studied company can be classified as a small company according to the criteria presented by Berisha and Pula (2015). The researcher played an active role in the studied company, having a good knowledge of his colleagues’ practices.

Table 14 - Action research protocol

Who were involved in the research		The researcher and the participant’s collaborators
Approach		Qualitative, verbal description of the phenomena observed.
Steps performed:	First Cycle	**Reflection**: Through the analysis of the case study and the artifact proposition conducted in the previous stages of the DSR. **Planning**: Design of the artifacts proposed **Implementation** (Act): Development of the artifacts **Evaluation** (Observe)**:** Evaluation of the Artifacts
	Second Cycle	**Reflection:** Analysis of the evaluation phase at the first cycle and suggestions of improvement in the artifact **Planning:** Design the improvements on the artifacts. **Implementation** (Act)**:** Development of the improvements on the artifacts **Evaluation** (Observe)**:** Expression of lessons learned
Analyse and interpretation of data		Participant observation, Seminars, interviews, and project’s documents

Source: The author.

The **Reflection** step in the first cycle was conducted through an analysis of the results of the case study performed in the Problem Awareness phase and the analysis of the artifact proposition performed in the previous sections of the DSR. The **Planning** step in the first cycle was the design of the artifacts, that indicated the techniques and tools for the development and evaluation of the artifacts. It also provided detailed information on the artifacts’ requirements, the artifacts’ internal characteristics, the context in which it would operate, its limits and relations with the external environment. Procedures for the development and evaluation of the artifacts were also described, as well as its expected performance. These assertions were to ensure the accuracy of the research allowing it to be replicated and confirmed.

The **Implementation** step in the first cycle was the development of the artifacts: At this point, the researcher, in a cooperative and participatory manner with participants, built the internal environment of the artifact. Several approaches were utilized such as computational algorithms, graphical representations, and models. The first cycle was closed with the **Evaluation** step when the researcher and the participant observed and measured the artifacts' behavior in regard to the solution of the problem. This evaluation was performed in an experimental environment in a real context. The researcher identified the topics which the artifacts did not meet the previously defined requirements.

The **Reflection** in the second cycle was conducted through an analysis of the results of the evaluation phase at the end of the first cycle. At this point, improvements were suggested. **Planning** in the second cycle consisted of revisions of the design of the artifacts in order to incorporate the suggested improvements. The **Implementation** step in the second cycle was a new development of the artifacts according to the improvements that were suggested. The **Evaluation** step in the second cycle corresponded to the observation and measurements the artifacts' behavior in regard to the improvements suggested in order to solve the problems identified in this research.

At the end of the second cycle, the lessons learned were expressed. At this point, the researcher declared the achievements and factors of success as well as the unsuccessful points and failures and the knowledge generated, both theoretical and practical. The aim of this step was to ensure that the research serves as a reference and aid for the generation of knowledge, both theoretical and practical.

3.7. Conclusion

At the **Conclusion** stage of the *Design Science Research,* the researcher formalized the results and the decisions made during its execution. The research limitations were reported, in order to be a guide to future researches. Some insights by the researcher were reported also, as they can lead to new problems and guide in future works. A summary of the research cycles with the knowledge gained with the artifacts is presented in two approaches. The first approach was the internal characteristics of the artifacts required for their proper functioning according to its external environment, their internal organization, taking into consideration its surroundings. The second approach is the external characteristics, the conditions of use of the artifacts with its limits, performance, and the suggestive context in which it can be useful.

4. CASE STUDY

Problem awareness is the second step in *Design Science Research.* In this phase, the researcher searches as much information as possible to ensure complete understanding of each factor and context of the problem and starts considering the functionality, operational requirements, performance and other characteristics of the artifact to be created. The case study method was chosen at this stage of the investigation because, according to Gil (2010) and Dresch *et al.* (2015), it is a suitable method for describing causal variables of a phenomenon in its environment.

This case study, conducted in parallel with the Systematic Literature Review, aimed to provide an overview of the problems identified in a broader context. The case study investigates issues faced by fabricators of engineered-to-order components that are typically small and medium-sized companies. Because their products are customized to fit the needs of a specific client or user, their manufacturing process is more demanding in terms of design specifications, and of sharing information between design and fabrication. Though engineered-to-order components fabricators are demanding for more sophisticated engineering, regularly those companies do not invest in research to improve the quality of their processes and products. Some of them have tried to improve their management processes by implementing solutions suited to mass production strategies.

4.1. Case study questions

Clients and users are increasingly demanding customized products, but the problems that engineered-to-order components fabricators have faced, cause the design and production costs to be high. This study aims to identify these problems. This case study starts with one generic question: What are the typical problems faced by engineered-to-order components fabricators? This question unfolds the specific questions listed in Table 6 case study protocol.

4.2. Selection of a case

This case study is within the bigger picture of implementing mass customization mediated by BIM. BIM enables essential process changes that provide the means to manage the immense amount of information required for mass customization. The subject studied in this investigation was a typical engineered-to-order building components fabricator that has manufactured with digital fabrication for over two decades. This study refers to a single and typical case that has the purpose of exploring and describing a company that is an ideal representative of its category. The studied company has some characteristics, described below, that makes it fit into a perfect case for this research's focus. It is a typical engineering-to-order strategy company specialized in the design and fabrication of customized cabinetry for kitchens, bathrooms, bedrooms, ensuites, closets, laundry rooms, powder rooms, and other living spaces.

We reinforce the reasons why Company A was chosen to be the subject of this case study. The **first** reason, which is one of the most important, is that this company offers customization at any phase of the process, starting from the design with the client actively involved, until the final installation that can be made by local staff or remote staff or yet by a third-party crew. The **second** reason is that this is a case of a subcontractor that fabricates engineered-to-order components for buildings, and according to Eastman *et al*., (2008), those companies are the ones that may have more to gain from BIM than any other participant in the building construction process. The **third** reason is that this company faces the generic problems cited in the previous paragraph. The **fourth** reason is that this company is a small enterprise, and the systematic literature review identified the lack of research on BIM and digital fabrication in small businesses. The **fifth** reason is that this company was willing to improve its manufacturing strategy, toward a Tailored Customization or even Pure Customization within the Mass Customization manufacturing system. Tailored Customization and Pure Customization according to the scale of Lampel and Mintzberg (1996), are the third and fourth levels of customization respectively. The **sixth** reason is that this company has offered for nearly 30 years, customized kitchens and other cabinetry components through a digital manufacturing process. Therefore, it is a good representative of its field in the context of this investigation. The **seventh** reason is that the researcher has a thorough knowledge of the company's organization, administration, design, and production processes. Therefore, he can act as a participant-observer in this case study. The **eighth** reason is that this company has a tradition of using and offering to the clients the cutting-edge technologies available in the market. The **ninth** reason is that this company has a commitment on a five-year unlimited product and installation warranty and a lifetime warranty on all hardware such as hinges, drawer tracks, pulls, and legs. Therefore, this is a good case for a study related to issues regards to product quality.

4.3. Data collection

According to Gil (2010), rigorous case studies require the use of multiple data collection techniques such as documents, interviews, and observations in order to ensure, through a triangulation, an in-depth study, adequate insertion of the case into its context and credibility of results. In this case study, documents related to every stage of production were collected, that is, documents from design, engineering, production, delivery, and installation. The researcher, as a participant-observer, played a role in generating some of those documents and developing software to generate and manage those documents. The collection of documents consisted of the full access to corporative databases, design drawings, bill of materials, purchase orders and invoices.

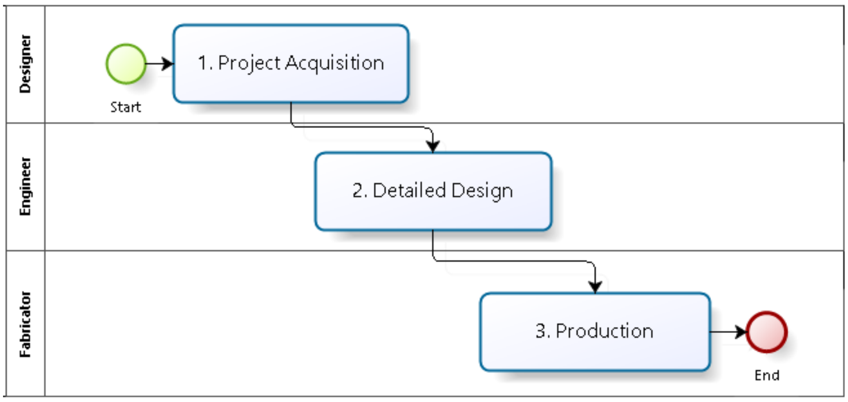
The second technique used for data collection was unstructured interviews that were performed in 2016 when the researcher played an active role in the process of design and production in the company. The interviews ordinarily started with an opening question and progressed based upon the initial response. They were generally time-consuming but very effective, especially when the interviewer had little knowledge about the topic or when a different perspective of a known subject was required. The interviewed personnel were both key people who knew deeply the company’s processes and had decision-making power as well as workers at the simplest positions.

The third technique used for data collection was participant-observation. The researcher was part of the group he was studying and had a deep understanding of the studied object, playing a strategic role in the integration of information and communication among design, engineering and production specialists. The researcher played different observational strategies: In some circumstances, the researcher was not noticed by participants. In other situations, the researcher had some limited interaction with the participants. But in most of the occasions, the researcher was fully partaking in the participants’ activities.

4.4. Data analysis and interpretation

Data collection and data analysis were performed simultaneously. Data validation was carried out through triangulation of data collected from interviews, observation, and documents. Regarding the study limitations, the research is more concerned with the aspects of processes and procedures and less with human resources aspects. As summarized in Figure 25, data analysis was performed through the grouping of the manufacturing process which comprises three basic processes related to the fabrication of engineered-to-order components.

Figure 25 - Macro processes in the cabinetry manufacturing strategy



Source: The author.

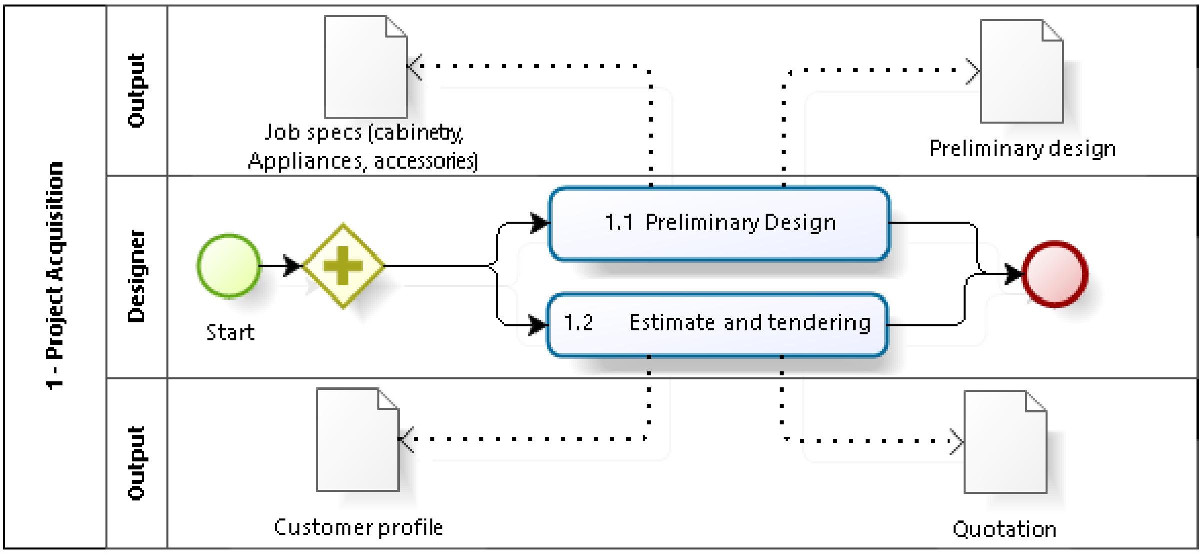
The first macro process observed was **Project Acquisition**, performed basically by the Designer or architect. Consultation meetings are scheduled so that designers can understand the client’s tastes, lifestyle needs and vision of a dream home. This consultation meeting includes site visits, design ideas, and budget estimate. The scope of work is defined, and a unique kitchen is articulated. The company's designers work closely with the engineers, craftspeople, and clients.

The second macro process observed was the **Detailed Design,** performed basically by the engineer. At this stage, experienced designers are scheduled together with project managers to create the design specified in the first stage. Intelligently zoned kitchens are designed to fit the specific needs of the client. The designing process is a blend of Tailored Customization and Pure Customization. The production process is a combination of handcrafted and automated systems. The definition of which parts of a project are handcrafted and which ones can be automatically manufactured occurs in the engineering phase. The detailed design process includes on-site measurements, cabinetry style, color and finishes, wood selection, built-in technology selection, and conceptual drawings of floor plan and views.

The last macro process observed was the **Production**, which is performed by the fabrication department or by a subcontractor that fabricates some special items such as drawers and doors. This department is a mix of the most advanced technology and old-style craftsmanship. This stage encompasses besides production, delivery of prefabricated components, on-site cabinetry installation, site visits to check for code compliance from regulatory bodies of the construction industry and the generation of “as-built” drawings that are useful for maintenance or upgrade purposes. The company deals with two types of suppliers: raw material supplier and finished items supplier. It has a just-in-time purchase system, that minimizes the inventory. This allows offering customers the advanced technological options available in the market.

The company offers also a site visit that is scheduled for six months after the project is complete. Figure 26 shows the **Project Acquisition** process map for the system of design and fabrication of cabinetry within the manufacturing strategy. The map holds one lane for the processes developed by the actors, which can be the in-house designer or architect plus the client’s technical representative, and two lanes to show the outputs of the process. The company has an in-house design team that works directly with the house owners or their technical representatives, whether they are designers, architects, engineers or contractors. To each job is assigned a designer and a project manager. Each job begins with two parallel processes, coded as “Preliminary Design” which is basically to get the job specifications and to generate the basic drawings, and the “Estimate and tendering” which are basically the quotation of the prospective job and meetings dedicated to understanding the client's needs and aspirations. Those parallel processes encompass consulting appointments between a designer from the company and the client or his architect or contractor. The designer gets all the information necessary for the program validation, that is, cabinetry material, style, finishing, appliances specs and list of accessories. Cabinetry finishings whether it is painted, stained or glazed are coded for future maintenance or for a product upgrade. This information allows the designer to prepare preliminary drawings that are useful also for job quotation. After the client approves the preliminary design, the designer performs the basic drawings.

Figure 26 - Project Acquisition process in the manufacturing strategy



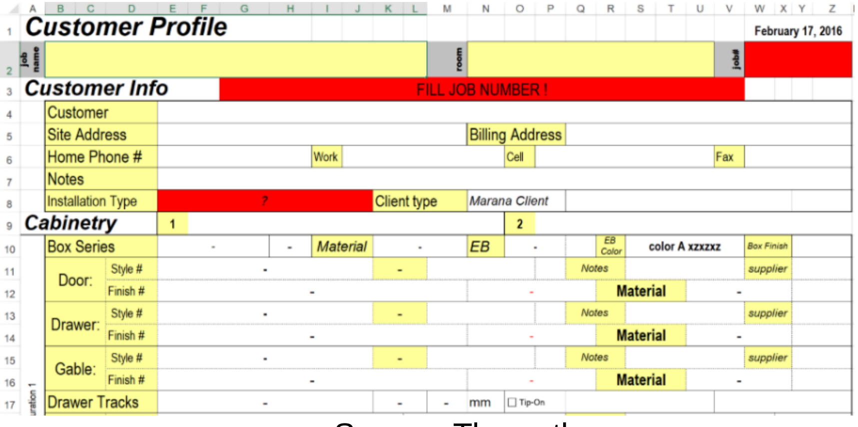
Source: The author.

A designer and a client discuss site options, lifestyle inventory, the formation of ideas on design, the project scope and budget estimate. The designer verifies constraints related to code compliance from regulatory bodies of the construction industry and generates the job specifications and a site layout that are sent to the client for approval. The designer also generates basic drawings using AutoCAD and creates two other documents: Customer Profile and Cabinetry configurations. These documents generated using Microsoft Excel spreadsheet programmed with *Visual Basic Applications* (VBA) are exemplified in Figure 27. The outputs of those processes are the first documents that are coded with a job number generated from the company's database. Loose papers are archived in a folder and documents generated in the computer are archived in a directory created for the job.

At the end of the **Project Acquisition** process, not only the site layout is configured as an intelligently zoned kitchen, but also the components are already defined and dimensioned basically through two strategies. In the first strategy, components are created based on small modifications made to a standard design to fit the client's need. In the second strategy, components are designed from scratch to fit a specific client's request. Those two strategies correspond to Tailored Customization and Pure Customization according to the classification of Lampel and

Mintzberg. Each cabinet can be manufactured with any width, depth or height and the client can specify box material, box edgebanding, box finish, door material, door style, door finishing, door supplier, drawer material, drawer style, drawer finishing, drawer supplier, and many other details such as crown, valance, pulls, countertop and glass door styles. Normally, a design is made by the combination of those two strategies described above and there is no inventory of finished products. Specifications of appliances such as fridge, range, oven, dishwasher, microwave, fan and sink are also obtained in the initial meetings with the client.

Figure 27 - Customer profile and cabinetry configuration



Source: The author.

Some issues were identified in the Project Acquisition phase:

- The efficiency in the process of producing and updating documents is weakened, when, by the time of the consultation meetings, clients don’t have yet all the necessary specifications on the appliances. Sometimes the information contained in the Preliminary Design documents and those from the quotation performed at the Estimate and Tendering phase are conflicting or missing, and a signed contract lacking technical information jeopardizes the detailing design.

- The accuracy and consistency of the documents generated at design are threatened when, despite the company's designers working closely with the engineers, craftspeople, and clients, information is stored in more than one document, or sometimes are missing. This causes conflicts and errors in later phases

- Innefficiencies in this phase increase the indirect costs.

Detailed Design is the second macro process in the manufacturing strategy shown in Figure 28. It is basically, the generation of documents for production. They are the detailed drawings and specifications of components by Tailored Customization and components by Pure customization. The main actors in those processes are the engineers. After the basic design is approved by the client or his representative, during the previous steps, the engineering department creates the production design detailed for production and the G-codes[12] for the Computer Numeric Control (CNC) machines. Inaccuracies and inconsistencies in the detailed design phase are discovered only in the production or installation phases of the job. This is caused mainly because the same information is registered into computers several times, each time for distinct use. In the Detailed Design macro process, documents are generated to fabricate some components at the shop floor or to outsource their production**.** At this stage, the system id divided into four parallel processes, namely, Engineering on Tailored Customization, Engineering on Pure Customization, Engineering on bought out components, and Preparation of shop drawings.

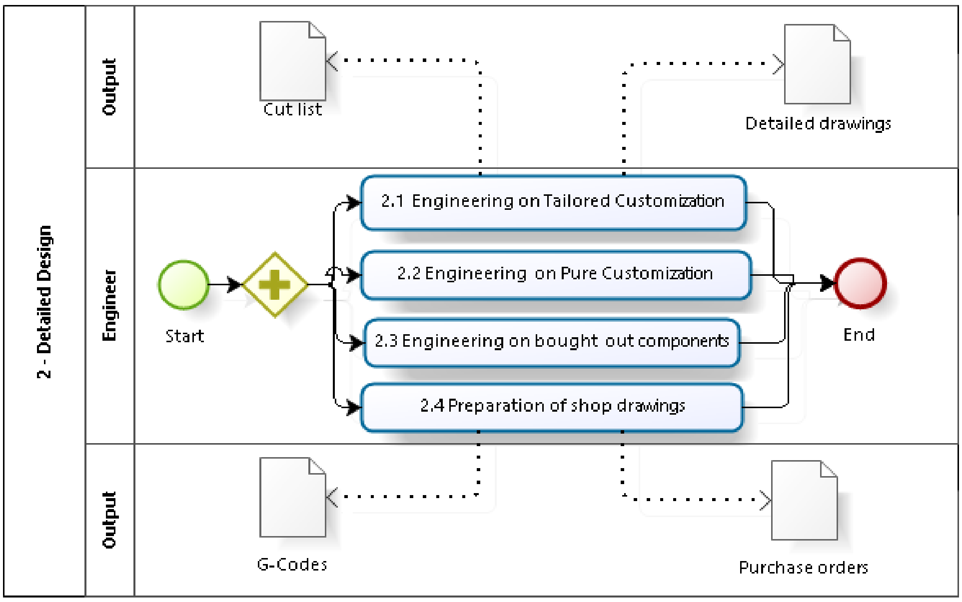
The **Engineering on Tailored Customization** allows small modifications made to the standard design in order to adapt the design to the client's needs. In this process, only the fabrication, assembly and distribution are customized. The Engineering on Tailored Customization comprises the generation of detailed documents from small modifications on standard designs. There is a library with a 3D AutoCAD drawing for each Tailored Customization component and a Microsoft Excel spreadsheet programmed with *Visual Basic Applications* with dimensions and specifications for each component. Some samples of those Tailored Customization components are depicted in Figure 29 that shows the 3D AutoCAD drawings, and in Figure 30. that shows the Microsoft excel spreadsheet with dimensions and specifications. it is available in the library, an average of 300 Tailored Customization cabinets and accessories, like, Light Panels, Kick base Platforms, columns, and fillers that can be quickly and efficiently manufactured in various sizes. In order to design the Tailored Customization cabinetry, the company uses a library of Tailored Customization components. The details for the fabrication of each piece, such as side panels, bottom, back, top, shelves, doors, drawers, legs, pulls, glasses and

[12] G-code is a common name for the programming languages for milling in the CNC machines.

hinges are prepared based on this library, as illustrated in Figure 30. The documents are both, a Microsoft Excel spreadsheet as depicted in Figure 30, and AutoCAD detail drawings as exemplified in Figure 31.

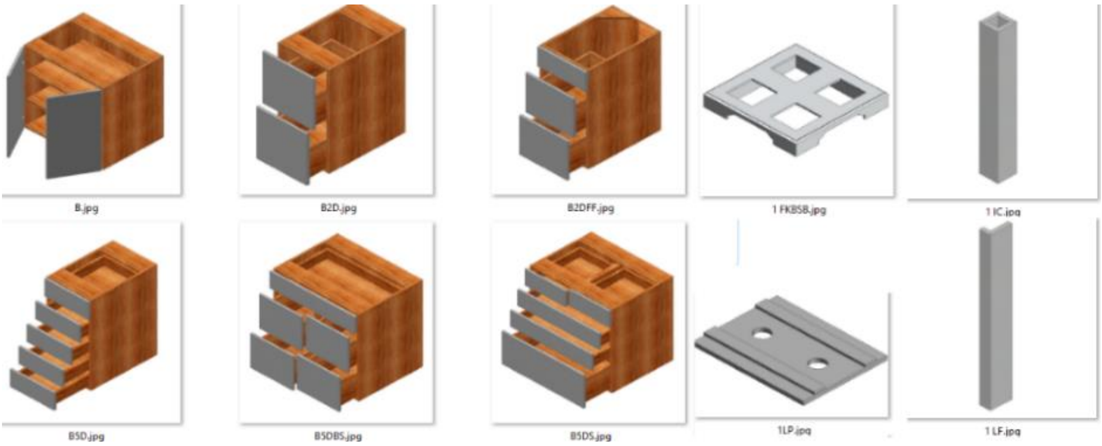
The **Engineering on Pure Customization** cabinetry is the process of generating detailed design documents for the customized components. It is mostly a handcrafted process that requires a large number of resources. Most of the labor effort in this phase is spent producing and updating drawings, bill of materials and purchase orders. The design of customized components is a time and cost consuming handmade work because each custom cabinet is “one of a kind” piece of art. The **Engineering on bought out components** is the process of generating the documents related to the components that are subcontracted and fabricated by a third party. They are some type of doors, drawers, and other components. For those items, purchase orders are generated with detailed specifications for fabrication. The **Preparation of shop drawings** for Tailored Customization components is automatic and pretty straightforward, but, the bottleneck in the whole system is the generation of shop drawings for customized components. Too many efforts are required for that because weaknesses in previous processes are reflected in this phase.

Figure 28 - Detailed Design process in the manufacturing strategy



Source: The author.

Figure 29 - Tailored Customization components sample



Source: The author.

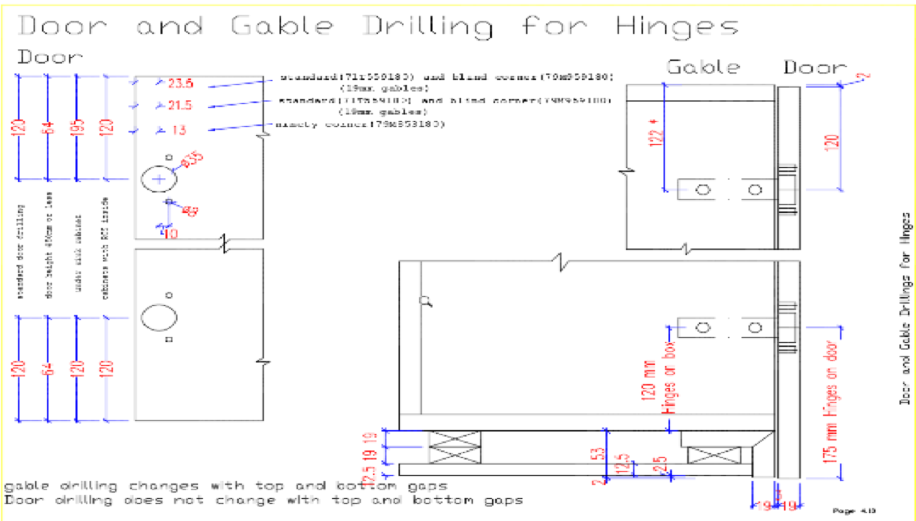
Figure 30 - Tailored customized cabinets' specifications, programmed in Microsoft Excel VBA

Item List Library

Row	Item	Quantity	Description – Cabinet Size W (af)	H (ag)	D (ah)	Hardware/ Subassemblies – Qty	Description	Details	Internal Width	Cut Parts (Saw / C – Item #	Part name	Qty	Finished sizes – Length	Width	Material	Thick-ness	Finish
13	1	1	800	748	622	4	Legs: 115-140mm #4511290			1	DoorL	1	743	397	-		-
14						2	Pulls:			1	DoorR	1	743	397	-		-
15	c1	5				4	Hinges O.L. 110 º - 71B359180			1	BLgbl	1	748	600	-		
16	L2	2	Base 2 doors							1	BRgbl	1	748	600	-		
17	R2	0								1	btm	1	800	600	-		
18										1	bk	1	748	800	-		
19										1	rails	2	800	140	-		
20										1	as	2	798	575	-		

Source: The author.

Figure 31 - AutoCAD Detail Drawings



Source: The author.

Several attempts have been made by the company to optimize the Detailed Design process, but with no success. Another problem in the system is the lack of consistency in the information among departments of sales, design, engineering, and production. For the cabinetry hardware, such as hinges, pulls, legs, lighting, and other accessories, purchase orders are automatically generated and sent to the supplier. Cut lists are generated for processing particle boards, plywood sheet and hardwood by the cutting machine. The engineer also generates G-codes for processing in the Computer Numerical Control (CNC) machines, and all the variables necessary for the elaboration of detailed drawings for the fabrication. Some of those variables are depicted in Figure 32, and they are, among others, box material, box thickness, door material, door thickness, drawer material, drawer thickness, the cabinet standard height, cabinet standard depth, plywood material code, plywood material thickness, edge tape material, edge tape thickness, gaps between boxes, gaps between shelves and door fronts.

Figure 32 - Fabrication variables

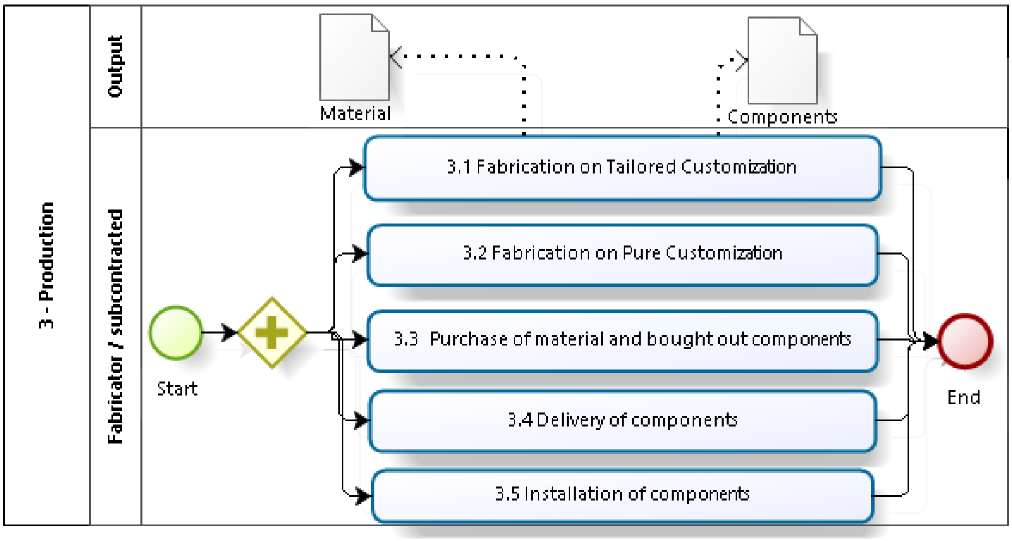
4	***Variables***		Configuration 1	Configuration 2
5	cells at this color must be changed in the customer profile			
6	**SHEETS (MATERIAL / THICKNESS)**			
7	**DOOR**	Door_Material	-	-
8		Door_Thickness	0	0
9	**DRW**	Drawer_Material	-	-
10		Drawer_Thickness	0	0
11	**GBL**	Gable_Material	-	-
12		Gable_Thickness	0	0
13	**CROWN**	Crown_Material	-	-
14		Crown_Thickness	0	0
15	**VALANCE**	Valance_Material	-	-
16		Valance_Thickness	0	0
17	**Drawer BOX**	DrawerBox_Material	-	-
18		DrawerBox_Thickness	16	16
19	**BOX**	Box_Material	-	-
20		Box_Thickness	0	0
21		Back_Thickness	0	0

Source: The author.

Production is the third macro process in the manufacturing strategy that is shown in Figure 33. It is basically the fabrication of each component of a project (enterprise). The main authors in this process are the craftsmen and the CNC machine operators, both, those who work in the company's shop floor and the ones who work for third-party companies. After the generation of detailed drawings, cut lists, G-codes and purchase orders, as described in the Detailed Design macro process, it takes place the Production macro process. Automation at CNC machines can occur in three stages of fabrication: (1) In the process of cutting the plywood and particle board sheets in a type of machine named Beam Saw, (2) in the process of gluing edge banding in panels in a type of machine named Automatic edge-banding,

(3) drilling and milling the plywood and particle board sheets in a type of machine named CNC Router. The automated manufacturing must have strategic planning, in order to minimize the number of setups in the CNC machines. At this stage, the system is divided into five parallel phases, namely, Fabrication of Tailored Customization, Fabrication on Pure Customization, Purchase of material and bought out components, Delivery of components, and, Installation of components.

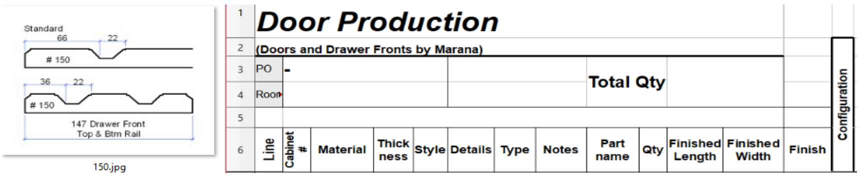
Figure 33 - Production process in the manufacturing strategy



Source: The author.

The **Fabrication of Tailored Customization** comprises the use of cutting-edge machine tools. The detailed drawings are inspected by the CNC machine operators. According to their style, Doors and Drawers can be fabricated as exemplified in the door production specification shown in Figure 34. The details for the fabrication of each piece, such as side panels, bottom, back, top, shelves, doors, drawers, legs, pulls, glasses and hinges have been prepared at the engineering on tailored customization phase. In order to manufacture the Tailored Customization components, the company uses digital fabrication technology, but the automated fabrication of Tailored Customization components, must have strategic planning, in order to minimize the number of setups in the CNC machines. Currently, the fabrication of customized components is a time consuming and costly handmade work, because of the programming efforts and set up time required of the CNC machines.

Figure 34 - Door specification

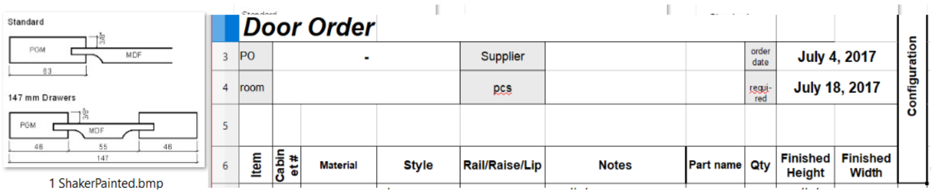


Source: The author.

The **Fabrication of Pure Customization** comprises the use of cutting-edge machine tools side-by-side with the traditional old-style handcrafts. The detailed drawings are inspected by the CNC machine operators, craftsmen, and other specialists. The automated fabrication of Pure Customization components, is time-consuming because it requires many setups in the CNC machines

The **Purchase of material and bought out components** comprises the generation of bill of materials with an online purchase order within a just-in-time logistics and a system of buy out components in which the specifications for fabrications are sent online to the subcontracted company. Depending on their style, Doors and Drawers can be ordered from third-party suppliers, as exemplified in the door order document shown in Figure 35, doors fabricated by third-party. Glass doors, glass shelves, and some countertop styles are also third-party supplied items.

Figure 35 - Door fabricated by third-party supplier



Source: The author.

The **Delivery of components** to the job site is a task that in the past were performed by the company but now these tasks are outsourced. After the completion of the parts manufacturing and the assembly of the modules, the items of a job are sent by a shipping company to the site for the final installation.

The **Installation of components** on the job site is a task that is performed by an in-house installation crew, and also by a third-party company. At the end of the installation process, a site visit is scheduled for six months after the project is complete, and “as-built” drawings are generated to be archived together with all technical specifications generated throughout all stages of conception, design, fabrication, delivery, and installation of the job. The “as-built” documents are intended to support the actions of the company in the event of litigations or to solve doubts regarding technical responsibilities throughout the job production. The design detailed drawings and “as-built” drawings are inspected by the assigned designer prior to a follow-up visit after installation. The cabinetry carries a five-year product and installation warranty plus a lifetime warranty on all hardware, hinges and pulls.

This case study described the design, engineering and production processes of engineered-to-order components under the Pure Customization and the Tailored Customization strategies. Considering the analysis and interpretation of data collected, it can be concluded that there is a lack of knowledge in implementing Pure Customization for manufacturing of engineered-to-order components. The studied company places a high value in providing customization of clients’ requirements at any phase of the process, starting from the design until the final installation, but its manufacturing system is not able to deliver the required Pure Customization level of manufacturing. Although the company can offer a Tailored Customization production strategy, at the level of design of engineered-to-order components, the system is a handicraft. After the analysis of these results compared with the conclusions from the Systematic Literature Review a hypothesis was formulated regarding benefits from Web-based BIM.

5. SYSTEMATIC LITERATURE REVIEW: Identification of artifacts

The objective of this SLR is to Identify and qualify existing artifacts in automated design and fabrication mediated by BIM for mass customization.

5.1. Search, Eligibility and Coding

The search was carried out simultaneously with its documentation. Search terms were constructed with the keywords defined in the protocol and submitted to the search engines of Emerald Insight, SCOPUS, Web of Science, American Society of Civil Engineers - ASCE library and *Biblioteca Digital Brasileira de Teses e Dissertações*. The keywords were defined in the exploratory research conducted prior to the Systematic Literature Review and they are: “BIM”, “Building Information Modeling”, “Fabrication”, “Mass Customization”, “Digital Fabrication”, “Design to Fabrication”, “Architecture”, “Manufactur*”, “Construction”.

From the above database sources, a set of studies were retrieved, archived and coded. 27 studies from Emerald, 98 studies from Scopus, 52 studies from Web of Science, 262 studies from American Society of Civil Engineers - ASCE and 45 studies from *Biblioteca Digital Brasileira de Teses e Dissertações*. After the exclusion criteria 1, 2 and 3 were applied through the analysis of titles, keywords and abstracts, the remaining studies were coded as potential studies, being 27 studies from Emerald, 32 studies from Scopus, 13 studies from web of science, 131 studies from American Society of Civil Engineers - ASCE and 35 studies from *Biblioteca Digital Brasileira de Teses e Dissertações*.

The potential studies received a deep full-text reading, in order to be applied the exclusion criteria 4,5,6,7 and 8. At the end of this process, the remaining studies were selected and coded: 9 studies from Scopus, 4 studies from Web of Science, 25 studies from American Society of Civil Engineers - ASCE and 7 studies from *Biblioteca Digital Brasileira de Teses e Dissertações*. To those, the quality assessment to determine the relevance of the study to the review question and the review focus was applied.

This process was recorded in a document named <u>Form for Conducting the Systematic Review</u>. The form contains the following information: Name of the electronic database source, name of the journal or title of the conference procedure, years searched, search string, URL for the search and list of reference of the studies found. For each combination of search engine plus search string, one form was created (in total 44 forms). Each form has not only the search history but also the exclusion criteria for each excluded study and they are depicted from Appendix B through Appendix F. For instance, the Form C01b shown in Appendix B is the search record made on November 14th, 2016, at the Emerald Insight database source, using the expression “BIM and Fabrication” as a searching string, narrowed by the content type (articles and books chapters) and by publication date (from January 1997 to November 2016). This specific search did not match any articles. But for the other searches were articles were found, the form has a list of references and a table with a code for each study. Later in the quality assessment, in case a study was considered not eligible for the synthesis of results, the exclusion criteria of the study were registered in that table. The process allows the Systematic Literature Review to be traced back.

5.2. Quality Assessment

After performing evaluations in each study according to the criteria specified in Table 9, the scores were consolidated to provide a general score to the study. The consolidation scale to measure each study was presented in Table 10 Studies evaluated as low quality according to this scale were excluded. Regarding this scale, it should be noted, that studies classified as low relevance to the review focus were evaluated as low quality for the research even in the cases that the quality of the study by itself was classified as high or the relevance to the review question was classified as high. This strictness is due to the effort on reducing the chances of bias.

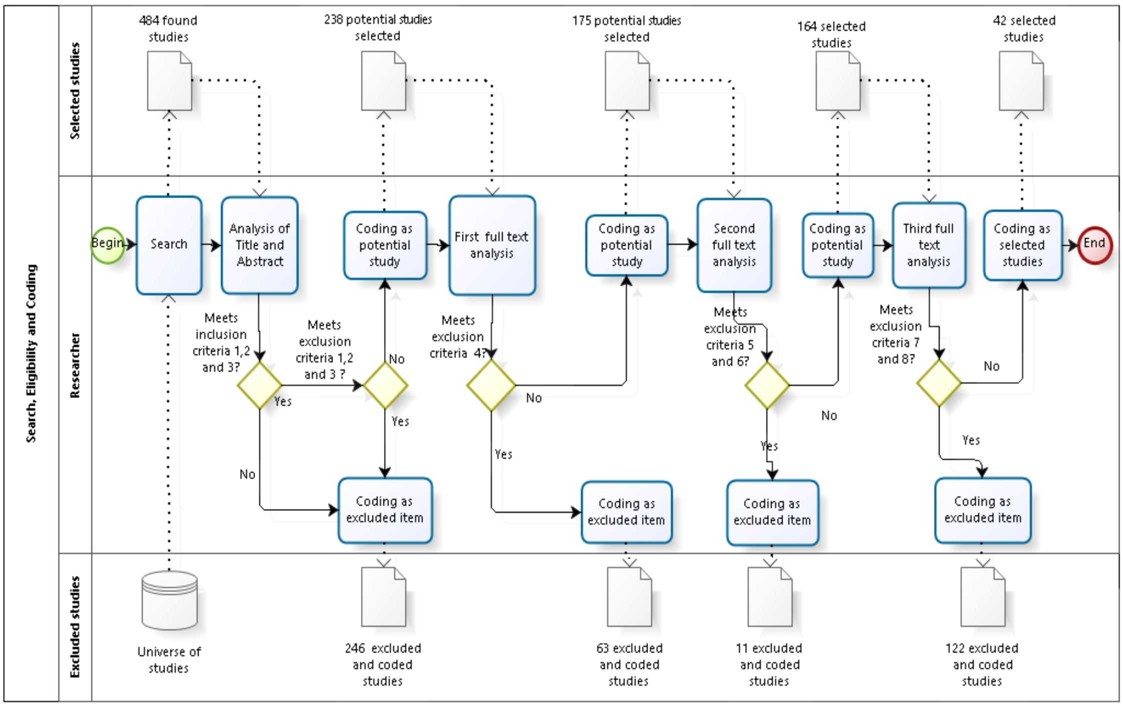
The sequence of search, eligibility, coding, and quality assessment activities in this Systematic Literature Review is depicted in Figure 36. Strings were constructed with the keywords defined in the protocol, submitted to the search engines (Emerald Insight, SCOPUS, Web of Science, ASCE library and *Biblioteca Digital Brasileira de Teses e Dissertações*), and from the broad spectrum of studies available, a set of 484 studies were retrieved, archived and coded. Next, inclusion and exclusion criteria were applied to determine the relevance of each study to the review. Excluded studies were archived and coded with the record of the reason for exclusion and studies that were considered relevant to the review were coded for use in the synthesis step. To the 484 studies found initially, an analysis of titles and abstracts and a full-text speed reading on each study was performed in order to apply the exclusion criteria 1, 2 and 3, that are: repeated studies, those whose full text is not available, and those not written in English or Portuguese. In this step, 246 studies were excluded.

The remaining 238 studies received an analytical reading for a deeper understanding. In this step, the exclusion criteria number 4 was applied, i.e., studies whose method is not explicitly proposed were excluded because they were evaluated as Low relevance according to the Criteria For Evaluation of the Quality of the Studies (see Table 9 and Table 10). Then the inclusion criteria number 4 was applied, i.e., studies evaluated as High or Medium by the Criteria for Evaluation of the Quality of the Studies. In this step, 63 studies were excluded, and 175 studies selected. The main inquiry at the first full-text analysis of those 238 studies was to verify if the research method was explicitly proposed.

Through a second full-text reading, studies had the exclusion criteria number 5 and number 6 applied, i.e., if the study did not follow the proposed method or if the results did not rely entirely on facts and data, it was excluded. The reason for this exclusion is that those conditions evaluate the study as LOW by the Criteria For Evaluation of the Quality of the Studies defined in the Protocol shown in Table 7. In this step, 175 studies received a deep reading, being that 11 studies were excluded, and 164 studies selected.

At the third full text reading, studies had the exclusion criteria number 7 and number 8 applied, i.e., if the study just mentioned the target subject or if the study was conducted in a different context to the one defined for the review, it was excluded. The reason for this exclusion is that those criteria evaluated the study as a LOW relevance to the review question or to the review focus. In this step, 164 studies received a deep reading, being that 122 studies were excluded, and 42 studies selected.

Figure 36 - Detail of the Search, Eligibility and Coding process



Source: The author.

Through the quality assessment, a data extraction form was filled for each study considered relevant to the investigation. The complete set of forms with all forty-two selected studies are documented in Appendix A and contain the following information: Artifact's description, artifact's type,[13] the results that the artifact cause, the kind of problem a study deals with, the artifact's constructive heuristics and contingency heuristics, context[14]; benefits[15], stakeholders[16], tools used in the development of the artifact, artifact's application[17], research center, research method, relevance to the review question, relevance to the review focus and study evaluation.

After the analysis and organization of available data, the studies were grouped into categories for the identification of patterns between them and the data integration. Then, existing artifacts and classes of problems were identified. Table 15 shows an example of one of those study that developed in the context of BIM and applied to construction components and evaluated as a medium relevance to this research.

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[13] Artifact' type:Construct, Model, Method, Instantiation or Design Proposition
[14] Context: BIM, Mass Customization, Digital Fabrication or Design to Fabrication
[15] Benefits:Produtivity, customization, interoperability or lifecyle integration
[16] Stakeholders: agents that might be interested in the study's subject in four groups: owner/facility manager, architect/engineer, Contractors and subcontractor/fabricator
[17] Application: construction components, interior design and architectural elements;

Table 15 - Example of a data extraction form

Reference	AHN et al (2016)
code	26C61b23
ARTIFACT	Description of organizational structures to maximize the benefits of BIM adoption
Artifact type	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	The most important areas where BIM has been implemented are MEP coordination, visualization, communication, marketing and site logistics / Challenging in reorganizing the company to take full benefits of BIM adoption. Organizational practice and transformation to enable to maximize the benefits and minimize the problems due to BIM adoption
HEURISTIC (Contingencial / Constructive)	The construction industry needs to develop a better understanding of how BIM can effectively integrate functions such as energy simulation, estimating, facility management and operation simulation / The research findings are beneficial for medium-size contractors who have a market in commercial offices, education, hospitals and multiresidential projects
Context:	BIM
Benefit	LIFECYCLE INTEGRATION: This study describes the organizational structure to maximize BIM inplementation throughout the project lifecycle
STAKEHOLDER:	Contractors
TOOLS: SOFTWARE / HARDWARE	
Application:	Construction components
Research center	Hanyang University, Korea; George Washington University, USA
Research methods	Case study
Relevance: Review Question	High
Relevance to Review Focus	Medium
Study Evaluation	Medium

Source: The author.

5.2.1. Artifact type integrating BIM, Digital fabrication and Mass Customization

The first research question for the Systematic Literature Review is: Which are the existing artifacts developed for the AEC industry, in the context of BIM, Digital fabrication and Mass Customization? Which are the stakeholders for each artifact?

Table 16 holds the studies grouped by artifact type and classified by their relevance to the review question and review focus. The analysis of the table shows that only one construct type artifact was classified as high in relevance to this investigation. The conceptual elements presented by Luth (2011) inspired the artifact's proposition of this investigation. In the opinion of Luth, the current IFC-based interoperability is jammed with graphical representations of database objects, and there is a need for what he has called “Fourth Generation Computer Technologies”, which is a simplified method for the database, containing the data describing the form, function, and behavior of the building. Luth suggests that if everyone would operate on the same database with a universal standard for schema and content, there would be no need for interoperability. Considering the Model type artifacts, eight studies were classified as high in relevance to this investigation. Among these, Goulding, Rahimian and Wang (2014), Khalili and Chua (2013), Anil, Unal and Kurc (2012), Chen, Reichard, and Beliveau (2010) and Lee et al. (2014) developed model artifacts that present solutions to problems related to interoperability. Three of them, Machado (2005), Rocha (2011) and Schneider (2014) developed model artifacts that present solutions to problems related to customization. Machado (2005) and Rocha (2011) describe Mass Customization implementation and Schneider (2014) develops a model to customize a product family for Mass Customization.

Girmscheid and Rinas (2012) developed the concept of “Cooperative world” describing the importance of a cooperative approach to lead the construction toward a higher level of prefabrication and customization. Rezgui and Miles (2010) developed a construct-type artifact that states that alliances allow small and medium enterprises to get a better reward for their work. Henriques (2013) developed a method of optimization and continuous improvement of the design process of steel constructions based on the concepts of mass customization. The study of Kim et.al. (2015) defines the principles for an appropriate selection of scaffoldings through a semiautomated use of scaffolding selection process, based on a predefined vocabulary for scafolding selection.

A linear relationship is a relationship where an independent variable is multiplied by a coefficient and added to a constant in order to determine a dependent variable. Among the model artifacts found in the review, Goulding, Rahimian and Wang (2014), Cheung, Kurul and Oti (2016); Ahn et al. (2016), Taylor and Bernstein (2016); Said (2015); Lee et al. (2014) present models with linear relationship type. Ahn et al. (2016) describe an organizational structure to maximize the benefits of BIM adoption. Cheung, Kurul, and Oti (2016) describes how to apply a marketing concept in the construction business. Goulding, Rahimian, and Wang (2014) created a web-based construction simulation environment. However, the study of Lee et al. (2014)

states that an object-relational database can improve interoperability, indicating a model with complex relationships. The studies of Taylor and Bernstein (2016) and Said (2015) stated that if the companies share their BIM files, they can achieve improvements in productivity.

Table 16 - Artifact type by study relevance-Reference

Artifact Type	Study Relevance			Artifact by study relevance – Reference	
	High	Medium	Total	High	Medium
Construct	1	4	5	Luth,2011	(Girmscheid, Rinas,2012) (Rezgui, Miles, 2010) (Henriques,2013) (Kim et al.,2015)
Model	8	10	18	(Goulding, Rahimian, Wang,2014) (Khalili, Chua,2013), (Machado,2005) (Rocha, 2011) (Schneider,2014) (Anil, Unal, Kurc, 2012) (Chen, Reichard,Beliveau,2010) (Lee et al. 2014)	(Cheung, Kurul, Oti,2016) (Ahn et al.,2016) (Taylor, Bernstein,2016) (Solnosky, Luth, 2015) (Girmscheid, Rinas,2012) (Said,2015) (Frutos,2006) (Chi et al.,2015) (Barak et al.,2009) (Ramaji, Memari,2016)
Method	4	8	12	(Gattas, You,2016) (Eastman et al.,2010) (Nawari,2012) (Venugopal,2011)	(Stavrić, Wiltsche,2012) (Duro-Royo, Mogas-Soldevila, Oxman,2015) (Lee, Kim,2012) (LEON et al.,2013) (Wang, Leite,2016) (Fettermann, 2013) (Frutos, 2006) (Wu, Issa,2015)
Instantiation	4	14	18	(Farr, Piroozfar, Robinson, 2014) (Gattas, You,2016) (Schneider,2014) (Anil, Unal, Kurc,2012)	(Sacks et al.,2010) (Jeong et al.,2009) (Khanzode, Fischer, Reed2008) (Duro-Royo, Mogas-Soldevila, Oxman,2015) (Lee, Kim, 2012) (Wang,Leite,2016) (Cao, Li,Wang,2014) (Morais,2011) (Fettermann, 2013) (Frutos, 2006) (Karaman,Ratnagaran,2013) (Hou et al.,2015) (Venugopal,2011) (Oswald,2014)

Source: The author.

A hierarchical relationship is a one-to-many relationship type in which variables are organized into a tree-like structure. Among the model artifacts found in the review, Solnosky and Luth (2015), Machado (2005), Chi et al. (2015), Barak Et al. (2009), Ramaji and Memari (2016), Chen, Reichard and Beliveau (2010) present models to enhance interoperability in the context of BIM, with hierarchical relationship type. Chen, Reichard, and Beliveau (2010) and Machado (2005) are studies classified as high relevance to the investigation. Chen, Reichard, and Beliveau (2010) develop a systematic definition of data structure and dependencies of interface information for modeling, and Machado (2005) describes catalysts factors of the implementation of Mass Customization.

A network relationship is when the relationships between variables are not restricted to being hierarchical. Among the model artifacts found in the review Khalili, and Chua (2013), Girmscheid and Rinas (2012), Frutos (2006), Rocha (2011), Schneider (2014), Anil, Unal, and Kurc (2012) present models with network relationship type. Khalili and Chua (2013) describe the BIM interoperability through an IFC-based model aiming to minimize the number of precast prefabricated structural elements. Anil, Unal, and Kurc (2012) describes the BIM interoperability through the requirements for simultaneous design and detailing of reinforced concrete structures. Girmscheid and Rinas (2012), Frutos (2006), Rocha (2011), Schneider (2014) developed models that deal with strategies in the context of customization.

Most of the methods found in the review are artifacts related to production. Gattas and You (2016), Eastman et al. (2010), Nawari (2012) and Venugopal (2011) developed methods to enhance interoperability in the context of BIM. The contribution of Gattas and You (2016) is a design-to-fabrication process for folded sandwich structures. The method developed by Eastman et al. (2010) captures detailed level information requirements from end-users at the IDM phase of the specification. The contribution of Nawari (2012) is a method that provides digital schema and provisions for efficient BIM application in the prefabrication industry. Based on a precast concrete component, Venugopal (2011), developed a method to validate a new approach to define Model View Definitions. Stavrić and Wiltsche (2012), Duro-Royo, Mogas-Soldevila and Oxman (2015) and Lee and Kim (2012) developed a method in the context of digital fabrication with benefits for customization. Stavrić and Wiltsche (2012) created a sequence of steps from design to fabrication of 3D ornamental parts by a robotic arm using 3D NURBS. Duro-Royo, Mogas-Soldevila, and Oxman (2015) created an integrated design and digital fabrication of multi-material and complex spatial objects, and Lee and Kim (2012) developed a stretch and bending method to fabricate mass customized double-curved metal panels. Leon et. al. (2013) developed a method to manufacture complex geometries integrating design and fabrication. Fettermann (2013) and Frutos (2006) developed methods associated with the development of products oriented to mass customization.

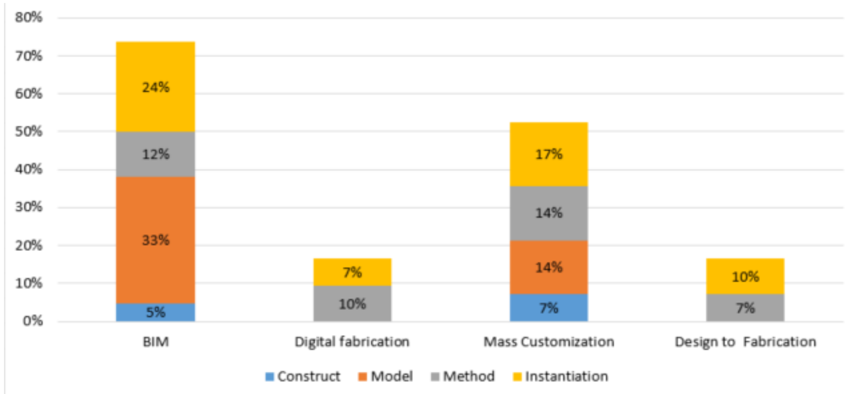
Instantiation artifacts operationalize and also demonstrate the feasibility of other types of artifacts. Instantiations show how to implement or use model type artifacts and method type artifacts. Anil, Unal, and Kurc (2012), Frutos (2006), Rocha (2011), Schneider (2014) and Venugopal (2011) present artifacts that verify the validity of Model type artifacts presented previously. Duro-Royo, Mogas-Soldevila, and Oxman (2015), Fettermann (2013), Gattas and You (2016), Lee and Kim (2012) and Wang and Leite (2016) present artifacts that verify the validity of Method type artifacts listed previously, and they use a wide variety of different tools in their experiments. There is not a single software or hardware that is used in more than one study. Cao, Li, and Wang (2014) validated the concept that different types of pressures[18] influences BIM adoption. Farr, Piroozfar, and Robinson (2014) and Sacks et al. (2010) tested the viability of BIM for design and fabrication of architectural precast facade. The studies of Hou et al. (2015), Jeong et al. (2009), Karaman and Ratnagaran (2013) and Khanzode, Fischer and Reed (2008) were experiments to validate the use of BIM to improve piping assembly, precast concrete structures, highway structures and the coordination of technically challenging MEP projects. The studies of Morais (2011) and Oswald (2014) were experiments on the digital fabrication of customized complex geometries.

Figure 37 shows that most of the existing artifacts are in the context of BIM or Mass Customization and there are few artifacts in the context of digital fabrication and design to fabrication. Lee and Kim (2012) is the only study that deals with mass customization and digital fabrication. They developed a method for stretch and bending double-curved metal panels. Morais (2011) is the only study that deals with Mass customization and Design to fabrication. It is an instantiation aiming to demonstrate that mass customization is economically promising. No Construct type or Model type artifact was found in the context of Digital Fabrication. No Construct type or Model type artifact was found in the context of Design to Fabrication. Digital Fabrication and Design to Fabrication are contexts yet to be explored by the academia related to BIM. This investigation has developed a Model and a Method in

[18] Coercive pressure is an effort made on organizations by other organizations upon which they are dependent.
Mimetic pressure is the one that drives organizations to imitate other successful organization that is structurally equivalent
Normative presure is derived from technology development. (CAO, LI and WANG 2014)

the context of Design to fabrication mediated by BIM.

Figure 37 - Artifact type by context



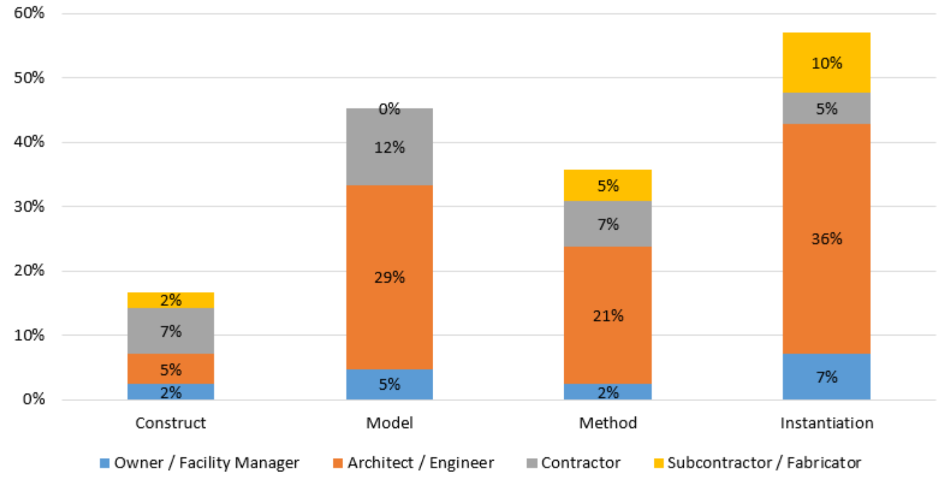
Source: The author.

According to Ahn et al (2016) reorganizing the company to take full benefits of BIM adoption is a challenge. Chen, Reichard, and Beliveau (2010) utilized the Unified Modeling Language (UML) to develop an Interface Object Model which defines the basic data structure to enhance interface modeling. Sacks et al. (2010) brings an experiment aiming to test the interoperability of BIM, obtained a productivity gain even with data exchange inconsistent and incomplete. From the studies applied to the contractors, some important statements are extracted. According to Rocha (2011), reducing the life cycle of products is favorable to customization strategies. Leon et al (2013) state that the integration of design and fabrication excludes the need for the mediation of drawings in the manufacturing process. According to Henriques (2013), standardized elements used with different forms of connection allow many customization configurations. In the opinion of Khalili and Chua (2013), the computation time in modeling increases exponentially with the number of elements in the model. Wang and Leite (2016) developed a method for capturing and representing discussions and decisions during the design coordination process because these information are useful in a building lifecycle. Wang and Leite say that in current practices process information is rarely documented formally.

Figure 38 shows that most artifacts are useful to architects and engineers and few studies were found related to the interests of Owners and Facility managers. Eastman et al. (2008) stated that subcontractors and fabricators of engineered-to-order components for buildings may benefit from BIM more than any other participant in the building construction process. However, this SLR demonstrated that this benefit is still not perceived.

Lee and Kim (2012), Jeong et al., (2009), Khanzode, Fischer and Reed (2008), Luth (2011) and Wang and Leite (2016) have Subcontractor and Fabricator as stakeholders.

Figure 38 - Artifact type by stakeholder



Source: The author.

5.2.2. Artifacts' Benefits

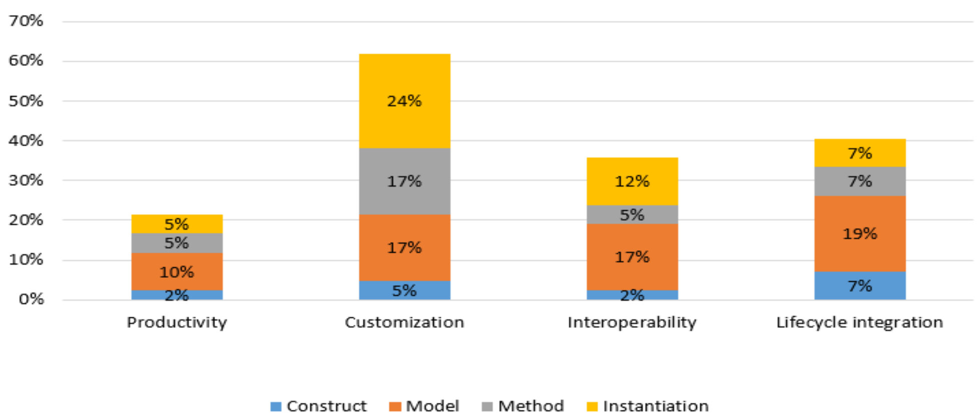
The second research question is: Which are the artifacts benefits in terms of productivity, customization, interoperability and life cycle integration? How are those benefits categorized by stakeholder and by artifact type?

Productivity, customization, interoperability and life cycle integration were considered by the researcher, the most relevant benefits related to the incorporation of BIM into an engineered-to-order manufacture of building components, aiming at Mass Customization. **Productivity** is the measure of the efficiency of a production system, i.e., the quotient between the amount of something produced, and the necessary inputs to produce. **Customization** is to create a product according to the client's needs. Customization requires the combination and arrangement of simple elements into more complex ones, in order to create a one-of-a-kind product that suits a particular need. **Interoperability** is the ability to transfer data from one application to another. It is the degree to which two software can exchange data among them. Interoperability is very important in the BIM context due to the fact that no single tool is able to perform all tasks related to a buildings model. The data format that is to be exchanged in a BIM context range from image file formats like JPEG to native BIM formats such as RVT going through file formats like IFC and CIS/2. **Lifecycle integration** is the combination of data from a building over its entire life, from the design phase to construction, operation, and demolition. The Lifecycle integration allows several types of analysis such as quality, maintenance, environmental, energy, artificial lighting, natural lighting and other types of analysis. This is a benefit that is important mainly to owners, because they need a more reliable source of information throughout the building lifecycle, in order to deal with cost overruns, unexpected costs, maintenance, and other issues.

In reading Figure 39 jumps out the fact that artifacts that provide benefits to enhance productivity were the least found. At the other end, the artifacts that provide benefits related to customization were the most found.

The categorization of benefits by artifact type in Figure 39 shows that most of the construct and model type artifacts identified in the selected studies are related to the lifecycle benefit, and most of the method and instantiation type artifacts identified in the selected studies are related to the customization benefit. The least amount of the construct, model, method and instantiation type artifacts identified in the selected studies are related to the productivity benefit.

Figure 39 - Artifact benefits by relevance



Source: The author.

Among all selected studies only Khanzode, Fischer and Reed (2008) addressed explicitly the benefit of **productivity** in the context of BIM. They carried out an experiment implementing BIM for the coordination of Mechanical, Electrical and Plumbing (MEP) systems in a highly complex project. They presented the challenges they faced, that includes, how to organize the project team, how to structure the coordination process and how to set up technical logistics.

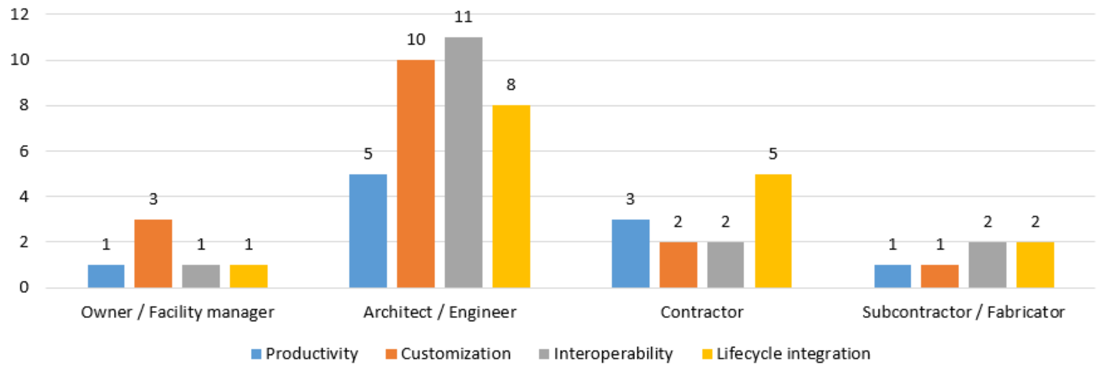
Among the selected studies who address the benefit of **customization** explicitly in their title, keywords or abstracts, Linner, and Bock (2012), Farr, Piroozfar and Robinson (2014) and Khalili and Kolarevic (2016) are studies evaluated as a high relevance to the Systematic Literature Review. They address concepts and models regarding the prefabrication housing industry. Fettermann (2013) and Schneider (2014) developed artifacts related to product development. Girmscheid and Rinas (2012) developed a concept related to a cooperative behavior among industry players as an approach toward the narrowing the gap in the highly fragmented construction industry. Lee and Kim (2012 developed a method for digital fabrication of double-curved unique facade panels. Morais (2010), Ramaji and Memari (2016) and Rocha (2011) developed artifacts related to customization strategies. Farr, Piroozfar, and Robinson (2014) did an experiment to investigate the benefit of BIM as a facilitator of customizable facades that was used to elucidate future developments and links to HTML and web database application. Linner and Bock (2012) developed a case study through a field survey in Sekisui Hem, a Japanese manufacturer of large-scale prefabricated houses. They verified that this company performs a manufacturing strategy which can be classified as Tailored Customization according to the manufacturing strategy criteria of Lampel and Mintzberg (1996). Khalili and Kolarevic (2016) developed a model that uses BIM to combine the parametrical variation needed in customization with the constraints required by code compliance from regulatory bodies of the construction industry. The authors concluded that a method of customer participation in the customization of housing must be developed and suggested that future researches could be dedicated to provide a higher level of customer participation in the building industry. Fettermann (2013) developed a method to identify and select tools and technologies related to the development of products oriented to Mass Customization, but this method is related to the development of products oriented to a Tailored Customization strategy. Schneider (2014) developed a two-stage model to customize product families.

Among the classified studies who address the benefit of **interoperability** explicitly in their title, keywords or abstracts, Newman et al. (2014) stated that interoperability in the manufacturing process can only become a reality if users’ pressures, force the vendors to integrate into their products a common platform. Tests for BIM data exchanges performed by Jeong et al. (2009), Khalili and Chua (2013), Sacks et al. (2010) and Karaman and Ratnagaran (2013) showed that despite progress in IFC much work is still needed to achieve fully effective interoperability. Sacks et al. (2010) add that many difficulties in data exchanges can be traced to a loss in translation semantic meaning.

Among the selected studies who address the benefit of **lifecycle integration**, Ahn et al. (2016), Ramaji and Memari (2016), Barak et al. (2009), Chi et al. (2015), Girmscheid and Rinas (2012), Goulding, Rahimian and Wang (2014) developed models that describe specific requirements to maximize BIM implementation throughout a project lifecycle. Girmscheid and Rinas added that a cooperative approach optimizes building lifecycle. Goulding, Rahimian, and Wang suggested the use of cloud-based technologies to enhance building lifecycle integration. Luth (2011) developed a construct-type artifact with the concept that simulation technologies based on a universal database are the future of design and construction engineering, though barriers to adoption of this new concept still abound on all sides. Rezgui and Miles (2010) developed a construct-type artifact specifically to small and medium-sized enterprises, stating that a group of partners interacting throughout a project lifecycle allows them to get a better reward for their work and gain financial strength. Stavric and Wiltsche (2012) addressed the lifecycle integration through design to fabrication approach integrated with digital fabrication.

As Figure 40 shows, most of the artifacts identified in the selected studies have architects and engineers as stakeholders. The studies that have subcontractors as stakeholders are Khanzode, Fischer, and Reed (2008) with benefits on productivity, Lee and Kim (2012) with benefits on customization, Luth (2011), Jeong et al. (2009) with benefits on interoperability and Luth (2011) and Wang and Leite (2016) with benefits on lifecycle integration. Owners, facility managers, and the contractors are stakeholders for whom just a few studies were found.

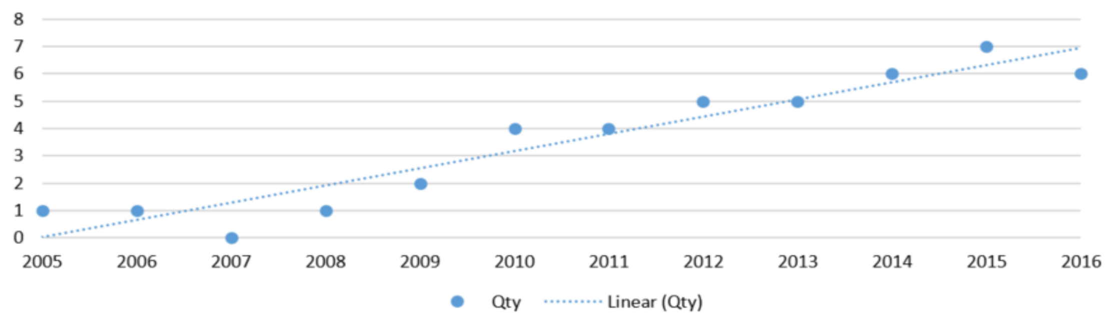
Figure 40 - Artifact benefits by stakeholder



Source: The author.

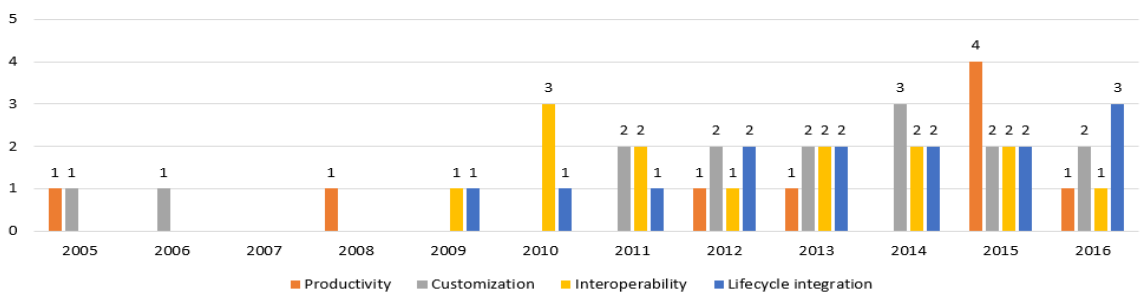
The upward bound curve shown in Figure 41 suggests that the review questions in this research are still getting the attention of the scientific community, and Figure 42. allow a more detailed analysis showing that before 2009, no interoperability and lifecycle integration artifacts were identified. Starting in 2013, artifacts related to all four benefits were identified. Since 2011, there is a steady interest in customization, interoperability, and lifecycle integration artifacts.

Figure 41 - Research evolved over time



Source: The author.

Figure 42 - Artifact benefits by year



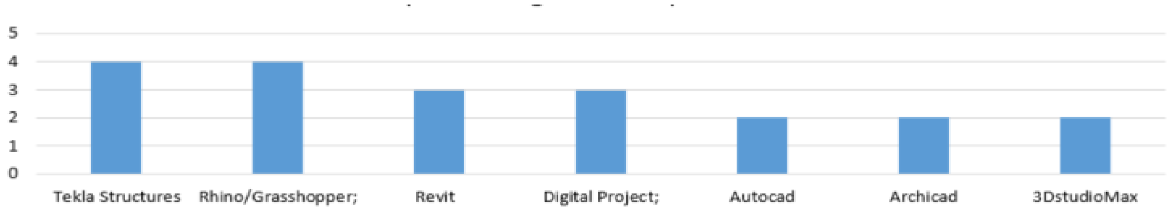
Source: The author.

5.2.3. Artifacts' supporting technology

The third research question is: Which are the artifacts supporting technology (software/hardware) and how can these tools be classified by benefits and by context?

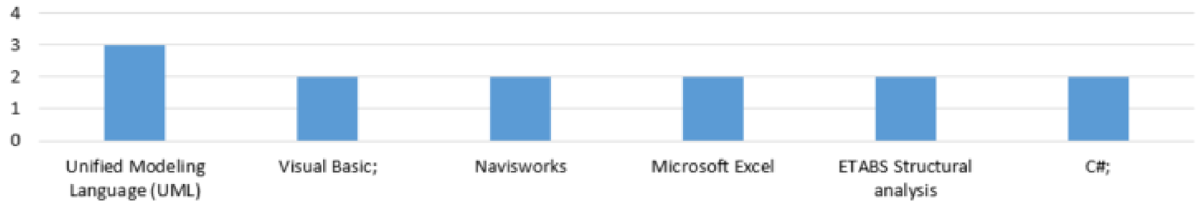
The most recurring modeling tools among the applied in the experiments of the selected studies are shown in Figure 43. Sacks et al. (2010), Jeong et al. (2009), Luth (2011), Karaman and Ratnagaran (2013) used Tekla structures. Goulding, Rahimian, and Wang (2014), Duro-Royo, Mogas-Soldevila, and Oxman (2015), Leon et al (2013), Oswald (2014) used Rhinoceros and Grasshopper. Sacks et al. (2010), Jeong et al. (2009), Khanzode, Fischer, and Reed (2008) used Revit. Jeong et al. (2009), Lee and Kim (2012), Leon et al (2013) used Digital Project. Jeong et al. (2009), Khalili and Chua (2013) used Archicad. Goulding, Rahimian, and Wang (2014), Morais (2011) used 3DstudioMax. The analysis and simulation tools that two or more among the selected studies have used in their experiments are shown in Figure 44. Wang and Leite (2016), Ramaji and Memari (2016), Chen, Reichard, and Beliveau (2010) used Unified Modeling Language (UML). Frutos (2006), Kim et al. (2015) used Visual Basic. Khanzode, Fischer, and Reed (2008), Wang and Leite (2016) used Navisworks. Fettermann (2013) and Frutos (2006) used Microsoft Excel. Khanzode, Fischer, and Reed (2008), Anil, Unal, and Kurc (2012) used ETABS Structural analysis. Lee et al. (2014), Anil, Unal, and Kurc (2012) used C#. Regarding sharing tools, Sacks et al. (2010), Khalili and Chua (2013), Karaman and Ratnagaran (2013) and Lee et al. (2014) used IFC (Industry Foundation Classes) schemes. No repository, processing, and fabrication tools were used by more than one study.

Figure 43 - Top modeling tools – Quantity of studies



Source: The author.

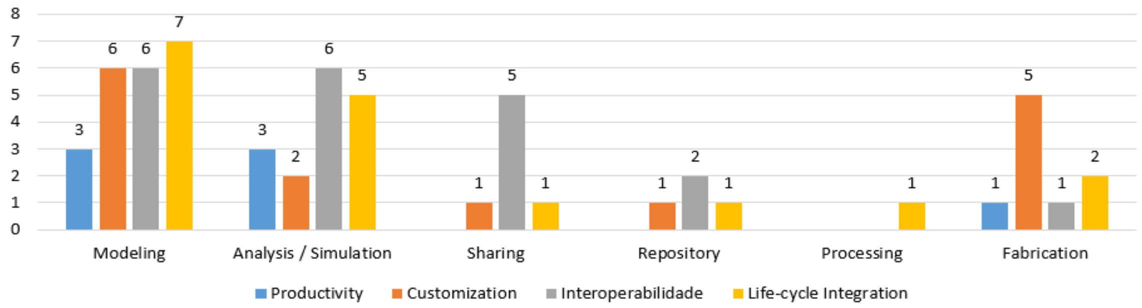
Figure 44 - Top Analysis / simulation tools – Quantity of studies



Source: The author.

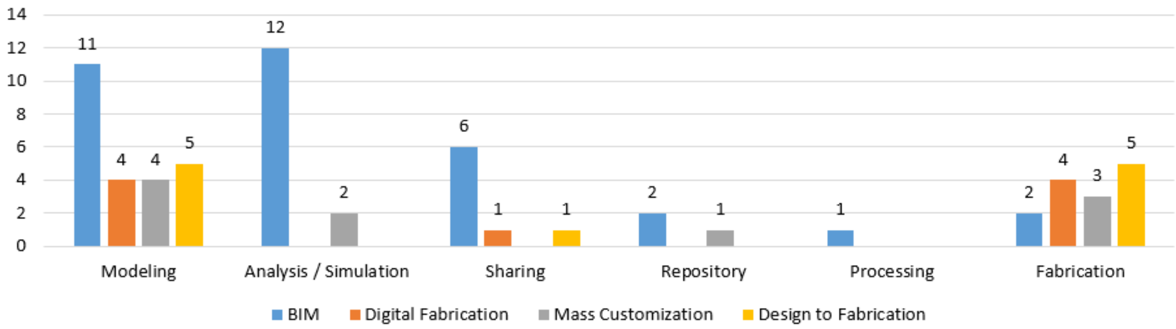
The comparison among artifact's supporting tools and benefits shown in Figure 45 allows the analysis that seven studies deal with sharing tools. Among those, only Duro-Royo, Mogas-Soldevila, and Oxman (2015) provide customization benefits and Khalili and Chua (2013) provide benefit for lifecycle integration. Jeong et al. (2009), Karaman and Ratnagaran (2013), Lee et al. (2014), Sacks et al. (2010), Venugopal (2011) used sharing tools in order to address issues on interoperability. Three studies deal with repository tools. Frutos (2006) provide customization benefit and Lee et al. (2014), Goulding, Rahimian, and Wang (2014) used repository tools in order to address issues on interoperability. Most of the tools used are related to modeling, followed by Analysis, simulation, and fabrication. The comparison among artifact's supporting tools and the context of the studies that used those tools shown in Figure 46 allows the analysis that seven studies deal with sharing tools. Among those, only Duro-Royo, Mogas-Soldevila and Oxman (2015) is a study in the context of design to fabrication through digital fabrication. Jeong et al. (2009), Karaman and Ratnagaran (2013), Khalili and Chua (2013), Lee et al. (2014), Sacks et al. (2010), Venugopal (2011) are studies that used sharing tools in the context of BIM. Three studies use repository tools. Goulding, Rahimian, and Wang (2014), Lee et al. (2014) use repository tools in the context of BIM and Frutos (2006) in the Mass Customization context. The complete list of artifact's software and hardware used in all selected study is presented in Table 17. The analysis of this table shows that there is not a pattern in the use of the different types of technology.

Figure 45 - Artifacts suporting tools by benefits



Source: The author.

Figure 46 - Artifacts suporting tools by context



Source: The author.

Table 17 - Artifacts supporting tools (continues)

Reference	Type		Description
Anil, Unal and Kurc (2012)	Software	Analysis	XML web services; Graphical User Interface: C#.net; structural analysis: ETABS v9.5
Barak Et al. (2009)	Software	Modeling	Georgia Tech process to product modelling GTPPM tool
CAO, LI, WANG (2014)	Software	Analysis	SmartPLS 2.0 M3 was employed as analysis program
Chen, Reichard, Beliveau (2010)	Software	Analysis	Unified Modeling Language – UML
Chi et al. (2015)	Software	Modeling	AVEVA
	Hardware	Fabrication	High-definition surveying scanner
LEON et al (2013)	Software	Modeling	Rhinoceros / Grasshopper; Digital Project based on Catia
	Hardware	Fabrication	CNC machines
Duro-Royo, Mogas-Soldevila and Oxman (2015)	Software	Modeling	Rhinoceros / Grasshopper; C-sharp code written to transmit XML instructions; Qt project; C code using IDE envirinment
	Software	Sharing	C-sharp code written to transmit XML instructions; Qt project; C code using IDE envirinment

Table 18 - Artifacts supporting tools (conclusion)

Reference	Type		Description
Duro-Royo, Mogas-Soldevila and Oxman (2015)	Hardware	Fabrication	6-axis robotic arm and a deposition platform: Kuka KR AGILUS model KR 10 R1 1000 SIXX WP
Fettermann (2013)	Software	Modeling	Promob Studio – moveis modulados
	Software	Analysis	Microsoft Excel
FRUTOS (2006)	Software	Analysis	JAVA Visual Basic; Microsoft Excel
	Software	Repository	ACCESS
GATTAS and YOU (2016)	Software	Modeling	MATLAB
	Hardware	Fabrication	2D CNC router
Goulding, Rahimian and Wang (2014)	Software	Modeling	Quest3DTM, EONReality, TM and Virtools, Autocad, 3DstudioMax
	Software	Analysis	MSProject, HTML, , ASP.net
	Software	Repository	MySQL
Hou et al. (2015)	Software	Analysis	Statistical Analysis Software – SAS
JEONG et al. (2009)	Software	Modeling	Revit; Archicad; Digital Project; Bentley Architecture, Tekla Structure; Structureworks precast
Karaman and Ratnagaran (2013)	Software	Modeling	finite element software; tekla Structures
KHALILI and CHUA (2013)	Software	Modeling	ArchiCAD and C#.net
	Software	Sharing	IFC
KHANZODE, FISCHER,REED (2008)	Software	Modeling	Autodesk Architectural Desktop, Revit Structure, QuickPen 3D Pipe Design, CAD Duct, SprinkCAD
KIM et al. (2015)	Software	Modeling	AutoCAD
	Software	Analysis	Visual Basic
LEE et al. (2014)	Software	Analysis	Mapping algorithm: CIS2SQL; C++; C#;
	Software	Sharing	IFC 2x3
	Software	Repository	CUBRID: object-relational database management system
Lee and Kim (2012)	Software	Modeling	Digital Project; a custom developed software application for the multipoint stretch forming machine
	Hardware	Fabrication	5-axis robot arm; laser cutting bed
LUTH (2011)	Software	Modeling	Tekla Structures
OSWALD (2014)	Software	Modeling	SAP 2000; Grasshopper/Rhinoceros
	Hardware	Fabrication	CNC milling machines
Ramaji, Memari (2016)	Software	Analysis	Unified Modeling Language (UML)
SACKS et al. (2010)	Software	Modeling	Revit, Tekla Structures
	Software	Sharing	IFC version 2x3
Stavrić, Wiltsche (2012)	Software	Modeling	Rhino / Grasshopper
	Hardware	Fabrication	industrial robot arm IRB 140 produced by ABB
Venugopal (2011)	Software	Sharing	EXPRESS: base language for IFC
WANG and LEITE (2016)	Software	Analysis	Autodesk Naviswork Manage; Visual Studio C#; Dot NET 3.5 Framework; Unified Modeling Language (UML)
	Hardware	Processing	PC with 1.60-2.7 GHz processor and 4-8 GB RAM; High resolution touch screen system
Wu and Issa (2015)	Software	Analysis	Business process model and notation (BPMN); Microsoft Visio

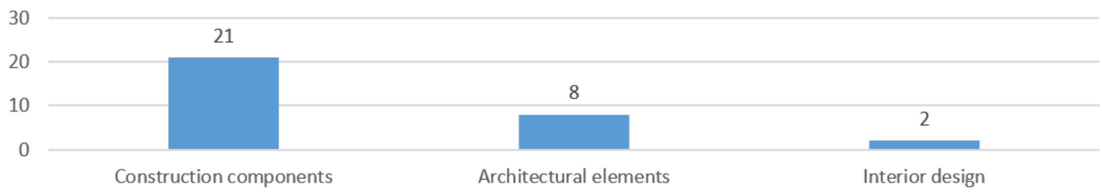
Source: The author.

5.2.4. Artifacts application

The fourth research question is: Which are the artifacts application in terms of construction components, interior design, and architectural elements? Each artifact application is in the interest of which stakeholders[19]?

Figure 47 shows that from the artifacts identified in the Systematic Literature Review, only two were applied to **interior design**. They are Fettermann (2013) and Machado (2005), that developed some artifacts applied to furniture. Among eight artifacts applied to **architectural elements**, Farr, Piroozfar, and Robinson (2014), Sacks et al. (2010) and Lee and Kim (2012) developed facades, and, Stavrić and Wiltsche (2012), Gattas and You (2016), Leon et al (2013), Duro-Royo, Mogas-Soldevila, and Oxman (2015) and Oswald (2014) developed complex geometric components, respectively, 3D ornaments, folded sandwich surfaces, hyperbolic geometries, mesh-free geometric primitives, and complex-timber. Among the twenty-one artifacts applied to **construction components**, Ahn et al (2016), Khanzode, Fischer and Reed (2008), Wang and Leite (2016) and Hou et al. (2015) were applied to mechanical, electrical and plumbing (MEP) components. Eastman et al. (2010), Jeong et al. (2009), Khalili and Chua (2013) and Venugopal (2011) were applied to precast concrete. Chi et al. (2015), Nawari (2012) and Rocha (2011) were applied in prefabrication. Anil, Unal, and Kurc (2012) and Barak et al. (2009) were applied to reinforced concrete. Kim et al. (2015), Karaman and Ratnagaran (2013), Luth (2011), Morais (2011) and Henriques (2013) were applied to steel structures. Chen, Reichard, and Beliveau (2010), Lee et al. (2014), Solnosky and Luth (2015) were applied to walls, slabs, doors, trusses, and other components.

Figure 47 - Artifacts Application



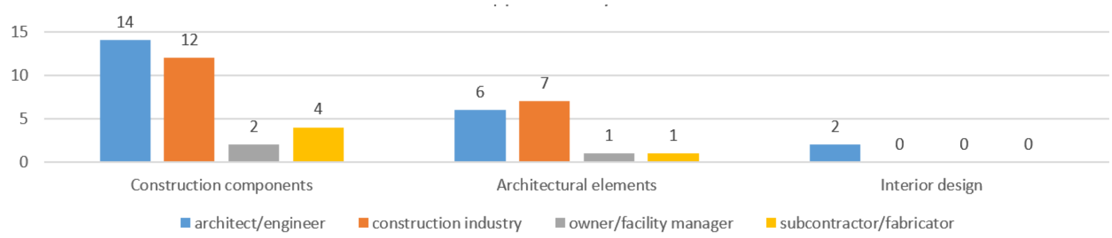
Source: The author.

Concerning the artifact's application by stakeholders that are shown in Figure 48, the majority of artifacts applied to construction components have architects, engineers, and contractors as stakeholders. The artifacts proposed in the

[19] In this systematic literature review, the stakeholders are grouped by (1) owner/Facility manager, (2)Architect/Engineer, (3)Contractors and (4)Subcontractor/Fabricator

fifth chapter are applied to interior design and have the subcontractors, as stakeholders. The subcontractors are involved with contractors and fabricators. It's worth noting that some studies are related to several groups of stakeholders. For example, the complex mesh-free geometric primitive architectural element developed by Duro-Royo, Mogas-Soldevila, and Oxman (2015) are related to architects, engineers, and Contractors. Also, the complex folded sandwich surfaces developed by Gattas and You (2016) are related to architects, engineers and Contractors.

Figure 48 - Artifacts Application by stakeholders



Source: The author.

Lee and Kim (2012) developed architectural elements whose stakeholders are subcontractor and fabricator. Jeong et al. (2009), Khanzode, Fischer, and Reed (2008), Luth (2011) and Wang and Leite (2016) developed construction components whose stakeholders are subcontractor and fabricator. Farr, Piroozfar, and Robinson (2014) developed architectural elements whose stakeholders are the owners or facility managers. Khanzode, Fischer, and Reed (2008) and Luth (2011) developed construction components whose stakeholders are the owners or facility managers.

In relation to the artifact's application in interior design studying Mass Customization strategies, Machado (2005) developed a case study on Todeschini; a company specialized in the production of furniture and cabinets for kitchens, bedrooms, living rooms, and bathrooms. The company is among the largest manufacturers of customized modular furniture in Latin America. Following are some excerpts from the study. The design is made with the software Promob following requirements specified by the factory. Usually, the design follows a pattern on a combination of standardized items from a catalog. The request of items not from the catalog are exceptions, but they can be granted as long as the production procedure do not escape routine. The customization in Todeschini takes place in the adjustment of dimensions of components such as countertops or shelves, but mainly in the combination of different items from a catalog. According to the criteria of Lampel and

Mintzberg (1996), the Customization process at Todeschini can be classified as Customized Standardization in which the assembly line is customized while the fabrication is not. The Artifacts developed in this research through an action-research, are intended to be applied in Tailored Customization manufacturing strategy according to the classification criteria of Lampel and Mintzberg (1996).

5.2.5. Research centers

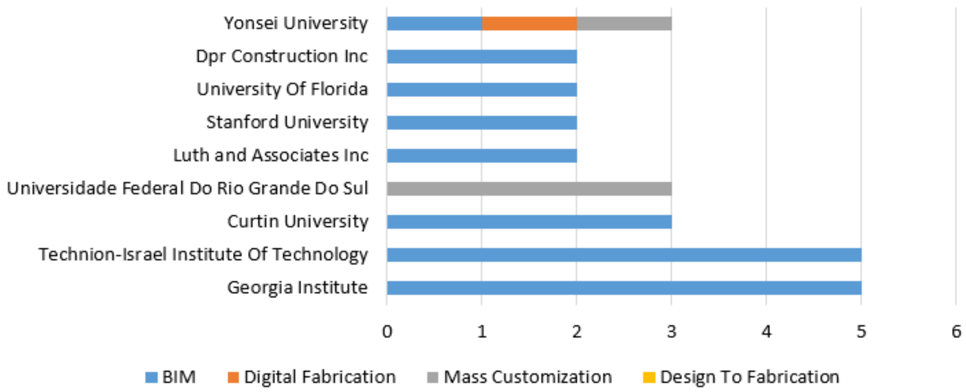
The fifth research question is: Which are the research centers involved in the development of the identified artifacts? What are the research methods used?

The majority of the research centers involved in the development of the identified artifacts have published only one study. Among the forty-two selected studies, there are forty-six different research centers. Only nine research centers are involved in more than one study. The research centers that published more than one study among the selected studies in this SLR were classified in this research as **Top Research Centers**. The remaining thirty-three research centers that have published only one study are listed in Appendix G. According to Figure 49, the prevailing context of the selected studies among the top research centers is BIM. Only Yonsei University has published in the context of digital fabrication and none of them has published in the context of design to fabrication. According to Figure 50, the prevailing benefit of the artifacts developed in the studies published by the top research centers is interoperability.

The Top research centers in descending order of quantity of publications are College of Architecture - Georgia Institute of Technology in Atlanta – USA, and, Faculty of Civil Engineering - Technion – Israel Institute of Technology in Israel. They have published five studies, namely, Sacks et al. (2010), Jeong et al. (2009), Eastman et al. (2010), Barak et al. (2009) and Venugopal (2011). School of Built Environment -Australia, has published three studies, namely, Goulding, Rahimian, and Wang (2014), Chi et al. (2015) and Hou et al. (2015). Engineering School in the Universidade Federal do Rio Grande do Sul- Brasil, has published three studies, namely, Fettermann (2013), Frutos (2006) and Rocha (2011). Luth and Associates – Inc, has published two studies, namely, Solnosky and Luth (2015) and Luth (2011). Dept.of Civil and Environmental Engineering - Stanford University in California, USA, has published two studies, namely, Khanzode, Fischer, and Reed (2008) and Kim et al. (2015). School of Architecture – University of Florida, USA, has published two studies, namely, Nawari (2012) and Wu and Issa (2015). DPR Construction Inc - USA, has published two studies, namely, Khanzode, Fischer, and Reed (2008), Kim et al. (2015). Yonsei University –Korea, has published two studies, namely, Lee et al. (2014) and Lee and Kim (2012).

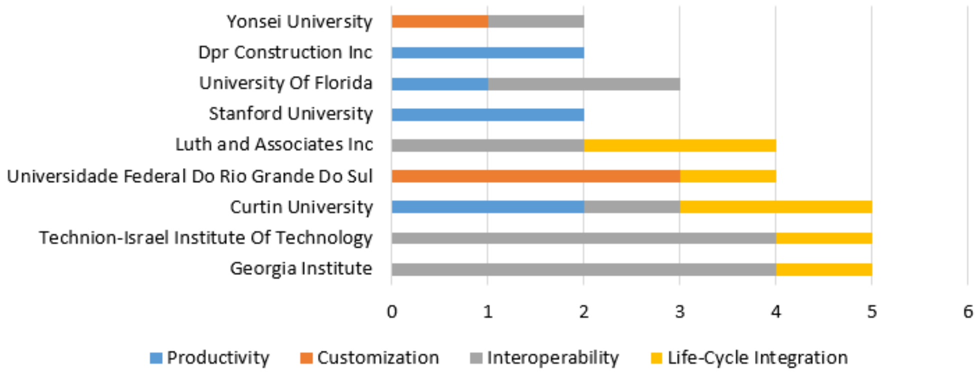
The prevailing research methods shown on Figure 51, are case study and experimental. Goulding, Rahimian, and Wang (2014) performed an Action Research with a management of production approach, Rocha (2011) performed a Design Science Research with a production process approach and Solnosky and Luth (2015) performed a Ground Theory with management of production approach. The studies developed by Anil, Unal, and Kurc (2012), Lee et al. (2014), Venugopal (2011) and Wu and Issa (2015) used Case study and Modeling methods. The studies developed by Farr, Piroozfar, and Robinson (2014), Karaman and Ratnagaran (2013), Khanzode, Fischer, and Reed (2008), Lee and Kim (2012) and Oswald (2014) used Case study and Experimental methods.

Figure 49 - Top Research Centers & context



Source: The author.

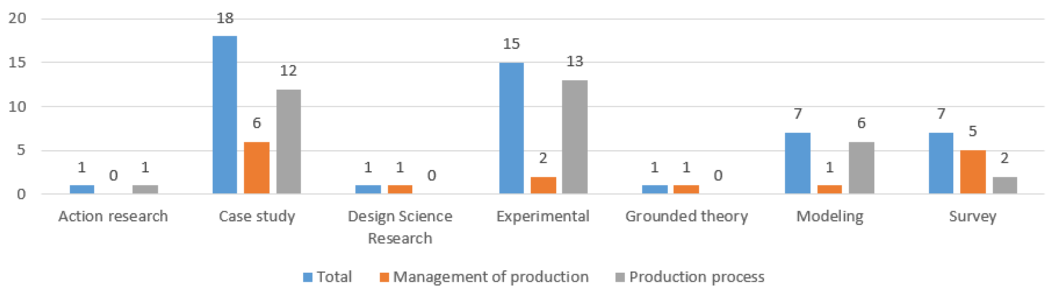
Figure 50 - Top Research Centers & benefits



Source: The author.

Figure 4.16 - Research Methods

Figure 51 - Research Methods



Source: The author.

5.3. Synthesis of results and Classes of Problems

The synthesis of results was split into three steps: The first one being the Analysis and organization of available data. The second one, the identification of patterns between them, and, the third one, the data integration. The synthesis began with the data extracted from the selected studies at the beginning of this chapter being tabulated containing the following information: Reference, problem, artifact, condition, and result. Patterns were identified in order to aggregate the problems into classes of problems. The complete set containing information on all selected studies is presented in the Appendix H, but five out from the forty-two tabulated studies are presented in Table 19, that present the studies that were classified as "**BIM adoption challenges**". Ahn et al. (2016) and Taylor and Bernstein (2016) looked into problems regarding to the reorganization of the company to implement BIM, being that Ahn et al. (2016) describes the organizational structure to maximize the BIM benefits, and Taylor and Bernstein (2016) developed a model artifact that describes a firm's trajectory as it gains experience using BIM tools. This trajectory progresses cumulatively in four levels, namely, Visualization, Coordination, Analysis and Supply chain integration. Wu and Issa (2015), developed a BIM model to address BIM in green projects, which could be classified according to the criteria of Taylor and Bernstein (2016) as the third level of BIM use, i.e., Analysis. Cao, Li, and Wang (2014) stated that BIM adoption is a highly socialized activity motivated not only by rational needs but also by external pressures. Though Poirier, Staub-French, and Forgues (2015) do not develop an artifact, this study was classified as relevant to the review, because it has a case study approach on BIM adoption, stating that Small-and-Medium-Enterprises (SME) and Specialty-Contractors can reap benefits from BIM if a clear strategy is implemented. There is a shortage of literature on BIM adoption for SMEs and specialty contractors (Poirier, Staub-French, and Forgues 2015). It is worth mentioning that the present investigation developed artifacts in the context of an SME company that is also a specialty contractor.

Table 19 - Studies related to BIM adoption challenges

Reference	Problem	Artifact	Condition	Results
WU and ISSA (2015)	The lack of standard processes to address BIM in green projects	Development of a BIM **process** model to improve green projects outcomes	The research is refined to focus on LEED projects	Improvement in the sinergy between BIM and green buildings
CAO, LI and WANG (2014)	How internal and external pressures can influence the BIM adoption	**Concept** that Isomorphic pressures influences the extent of BIM adoption	Empirically tested with survey data collected from 92 chinese construction projects	BIM adoption is a highly socialized activity motivated by rational needs and external pressure.
AHN et al (2016)	Challenges in reorganizing the company to take full benefits of BIM adoption.	Description of **organizational structures** to maximize the benefits of BIM adoption	Medium-size contractors	Organizational structure to maximize BIM inplementation throughout the project lifecycle
TAYLOR and BERNSTEIN (2016)	How organizations evolve internally and externally with the use of BIM	**A model** that describes a firm's trajectory as it gains experience using BIM tools	BIM practice evolve cumulatively in a four-level trajectory	Levels of BIM uses: Visualization, Coordination, Analysis, Supply chain integration
POIRIER, Staub-French and Forgues (2015)	The lack of literature on adoption of BIM for SMEs and specialty contractors	no artifact	Case study approach on BIM adoption	SMEs and specialty contractors can reap benefits from BIM if a clear strategy is implemented

Source: The author.

Lampel and Mintzberg (1996) stated that a manufacturing company has four stages in its value chain, i.e., Design, Fabrication, Assembly and Distribution. The extent to which each stage is customized or standardized gives way to five different strategies, i.e., Pure Customization, Tailored Customization, Customized Standardization, Segmented Standardization, and Pure Standardization. The first four strategies are considered levels of customization, in which the highest level is the Pure Customization that offers customization in all four stages of the manufacturing process. According to Khalili and Kolarevic (2016), true customization requires the participation of customers in the design stage, but the customization that designers usually offer is a selection among standard designs. The challenge of customer participation in design is the need of a constraint-based design system in order to ensure checking with code compliance from regulatory bodies of the construction industry.

In spite of the importance of design in the customization context, among the seven studies presented in Table 20, that were classified as “**Design challenges**”, only Schneider (2014) and Farr, Piroozfar, and Robinson (2014) are investigations in the context of customization. Both, with different approaches, claim that BIM can smooth the customization process. Schneider (2014) states that the design of a product family is a difficult task, but once it is done, to derive members of the product family to create an instantiation of a client’s requirement is a simpler task, and he developed a framework to customize a product family. Farr, Piroozfar, and Robinson (2014) tested the design of customizable facades through the development of a product family under three systemic levels, named super-system, system, and subsystem. Luth (2011), Goulding, Rahimian, and Wang (2014) and Karaman and Ratnagaran (2013), with three different approaches, examined the design challenges in the context of interoperability issues. In their opinion, due to the fragmented context of the contractors, the interoperability among systems is very complex and there is a need for an easier data exchange system. In the opinion of Luth (2011), every BIM model should be independent of the software, operating on the same database. There would be no need for interoperability. Goulding, Rahimian, and Wang (2014) suggest web-based platforms for sharing information. Leon et al. (2013) and Gattas and You (2016), they all deal with design challenges specifically regarding fabrication. Leon et al. (2013) seek to narrow the gap between design and fabrication developing a method for manufacturing complex geometries, and Gattas and You (2016) seek to increase the feasibility of digital construction through the design and fabrication of an origami-like structural form.

Table 20 - Studies related to design challenges

Reference	Problem	Artifact	Condition	Results
LEON Et Al (2013)	The gap between design and fabrication	**INSTATIATION**: Automated digital design for production	Manufacturing of Hyperbolic geometries and their complex intersection	Flexible automation in the integration of CAD/CAM
GATTAS And YOU (2016)	Increase feasibility of digital construction	**METHOD**: Design-to-fabrication process for folded sandwich structures.	Limitations: non-uniform building structures.	a design-to-fabrication process for folded sandwich (origami-inspired) structures
Luth (2011)	The complexity of interoperability in the fragmented discipline context of the Construction industry .	Refinements to the **definition** of construction and design engineering	“If the database follows a universal standard for schema and content, there is no need for interoperability – everyone operates on the same database” page 914	A BIM model should be independent of individual software packages and graphical interfaces
GOULDING, RAHIMIAN And WANG (2014)	Sharing information for geographically dispersed end users	**A model** for web-based environment for a construction site simulation	Collaborative teams. Web-basedsystems	Web-based platform for sharing information
KARAMAN And RATNAGARAN (2013)	The error-prone nature of tolerance accumulation	3D **parametric description** of highway geometry suitable for data-exchange integrity	Curved steel bridge design, detailing, fabrication and erection	Interoperability requires standardization in software data exchange
Schneider (2014)	The design of a product family is a difficult and challenging task	**A formal approach to model** the customization of product families	Product family is a key concept of mass customization	To derive members of the product family to customize a client's requirement can be a simple task
Farr, Piroozfar and Robinson (2014)	The challenge of achieving mass customization	**INSTATIATION**: mass customizable facades using a BIM application	Customisable façade systems.	The concepts of 'Super-System','System' and 'sub-system'

Source: The author.

Among the studies presented in Table 21 and Table 22, classified as “**Mass Customization challenges**”, Lee and Kim (2012) and Linner and Bock (2012) deal with problems in fabrication. Lee and Kim (2012) developed a method to manufacture double-curved unique panels while Linner and Bock (2012) presented a description of the Japanese cultural, economic, and technological context of the large-scale prefabricated house industry. Some artifacts related to the design of a product for mass customization were developed by Farr, Piroozfar, and Robinson (2014), Fettermann (2013), Frutos (2006) and Schneider (2014). In the opinion of Fettermann (2013), Mass Customization requires products with short lifecycle, and Rocha (2011) suggests the use of high technology tools to reduce the lifecycle of goods. Farr, Piroozfar, and Robinson (2014) who presented the concepts of 'Super-System', 'System', and 'sub-system' applied to the customization of façade. According to Schneider (2014), the design of a product family is a difficult and challenging task. Girmscheid and Rinas (2012), Henriques (2013), and Rocha (2011) developed artifacts related to processes in the fabrication stage of manufacturing. Cheung, Kurul, and Oti (2016), Khalili and Kolarevic (2016), Machado (2005) developed artifacts related to processes in the design stage of manufacturing.

Table 21 - Studies related to Mass customization challenges (continues)

Reference	Problem	Artifact	Condition	Results
CHEUNG, KURUL and OTI (2016)	weak communication between stakeholders	Description of the application of a marketing concept (Service-dominant logic) in construction business	Comparison of focus, benefits and issues between mass production and mass customization	illustrate how apply marketing strategies to enrich communication in AEC industry
Farr, Piroozfar And Robinson (2014)	The challenge of achieving mass customization	mass customizable facades using a BIM application	The object oriented programming concept of inheritance can facilitate the customization	The concepts of 'Super-System','System' and 'sub-system' applied to the customization of façade
FETTERMANN (2013)	Como Desenvolver Produto orientado a customizacao em massa	Metodo para desenvolvimento de produto orientado a customizacao em massa	A reducao do tempo de set up das maquinas CNC auxilia a Customizacao em Massa	Customizacao em Massa requer produtos com curto ciclo de vida
FRUTOS (2006)	Como interagir com o cliente na configuracao de produtos em customizacao em massa.	Metodo colaborativo que oferece um conjunto de passos para facilitar a configuracao de um produto customizavel	Programacao Orientada a Objetos, Analise de decisao multiatributos e programacao linear de inteiros.	integracao entre especificacoes do cliente e limitacoes tecnicas em customizacao em massa
GIRMSCHEID and RINAS (2012)	How to deal opportunistic behavior in complex systems	A design model for industrialization in construction	A cooperative approach	enables mass customization in the prefabrication industry

Source: The author.

Table 22 - Studies related to Mass customization challenges (conclusion)

HENRIQUES (2013)	projeto e producao em aco com caracteristicas artesanais	Metodo de projeto de construcoes metalicas com conceitos de customizacao em massa	Utilizacao de projetos padronizados com diferentes configuracoes de conexao	sistema estrutural modulado para edificacoes customizadas em aco
KHALILI and KOLAREVIC (2016)	The challenge of customer participation in Mass customization	A method for a customization parametric design based on constraints	designers must move from customization based on selection among standard designs	Participation of customers im design
LEE and KIM (2012)	The challenge of mass customization of double-curved metal panels	Stretch and bending method to fabricate mass customized double-curved metal panels	Precision and a limited budget and schedule as key requirements.	an affordable and fast technique to fabricate double-curved unique panels
LINNER and BOCK (2012)	What are the concepts related to the papanese industry	no artifact	Case study approach in the japanese cultural, economic and technological context	Description and analysis of japanese large-scale house-industry
MACHADO (2005)	Identificar fatores desencadeadores e habilitadores da adocao de customizacao em massa	Modelo descrevendo fatores catalizadores da implementacao de customização em massa(CM).	Analise das estrategias de CM executadas por empresas brasileiras	O contexto do mercado, as caracteristicas do produto e o processo produtivo influenciam a decisao de implantar CM
ROCHA (2011)	The fragmented body of knowledge and the shortage of prescriptive support on Mass Customization	A sequence of steps for defining a customization strategy for house-building sector	A short product life cycles creates a turbulent market, but is the ideal environment for customization.	A high rate of technological changes reduces the life cycle of products
SCHNEIDER (2014	The design of a product family is a difficult and challenging task	A formal approach to model the customization of product families	Product family is a key concept of mass customization	To derive members of the product family to customize a client's requirement can be a simple task

Source: The author.

Through this SLR, the existing knowledge and artifacts related to the impact of BIM in the context of Mass Customization were carried out. The artifacts were summarized into three classes of problems. BIM adoption challenges, Design challenges, and Mass customization challenges. Considering the analysis of the existing artifacts together with the analysis and interpretation of data collected in the case study[20], that concluded that there is a lack of knowledge in implementing Tailored customization[21] and Pure Customization[22] strategies for manufacturing engineered-to-order components in SME companies, and this corresponds to the main hypothesis of this research could be formulated, that is to say, fabricators of engineered-to-order components can achieve Mass Customization with the mediation of a Web-based BIM technology.

Hamid, Tolba, and Antably (2018) demonstrated a way in which the semantics of design and fabrication of engineered-to-order components could be incorporated into BIM objects and how these BIM objects could be used to support the workflow between design and fabrication, specifically digital manufacturing of custom cabinetry. The main contribution of their research was to clarify some aspects related to BIM and CNC technologies working together. In addition to the well-known BIM benefits related to accurate visualization, consistency between views, and the generation of automated reports in the design phase, they discussed some other important aspects: (1) the ability that the knowledge embedded in the BIM objects provided to automatically validate dimensional variations for parts during design exploration; (2) the ability for the designer to select a suitable material finishing without the need to refer to a static catalog, and; (3) the usability of design deliverables and fabrication knowledge embedded into BIM objects to benefit the fabricator. The exporting procedure they adopted was to transfer the fabrication knowledge from the BIM objects to the CNC machines through DXF files based on rules in the layer naming. They discussed also some challenges they faced: (1) the amount and complexity of the parameterization required for Engineered-To-Order manufacturing; (2) the limits of the transfer of fabrication parameters through DXF files; (3) issues regarding the intellectual security of the elicited knowledge embedded into BIM models; (4) a communication shortage between designers and fabricators.

Among the Critical Success Factors (CSF) used to measure a successful

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[20] The case study is detailed in the Problem Awareness chapter.

[21] Tailored Customization is a manufacturing strategy according to the criteria of Lampel and Mintzberg (1996), in which small modifications are made to a standard design to adapt it to the client's needs. In this strategy only the fabrication, assembly and distribution are customized.

[22] Pure Customization is a manufacturing strategy according to the criteria of Lampel and Mintzberg (1996), that the design is made according to the customers specifications. It offers customization in all four stages of the manufacturing process; Design, Fabrication, Assembly and Distribution.

BIM implementation are: (1) Enhancing exchange of information and knowledge management; (2) Verification of consistency to the design intent; (3) Ensuring effective communication among project participants; (4) Collaboration in design, construction, and engineering stakeholders; (5) Providing BIM models for shop drawings; (6) Providing BIM models for offsite prefabrication; (7) Accuracy and reliability of data leading to less reworking and fewer document errors and omissions (ANTWI-AFARI et al., 2018).

6. ARTIFACTS PROPOSITION

The fifth step of the design science research is the proposition of artifacts, which is essentially creative. Besides creativity, the identification of existing artifacts in the previous step plus the researcher's knowledge and practical contact with, and observation of the problem, guides, through abductive reasoning, the suggestion of a solution. In this research, the solution comprises four artifacts that were developed through deductive reasoning.

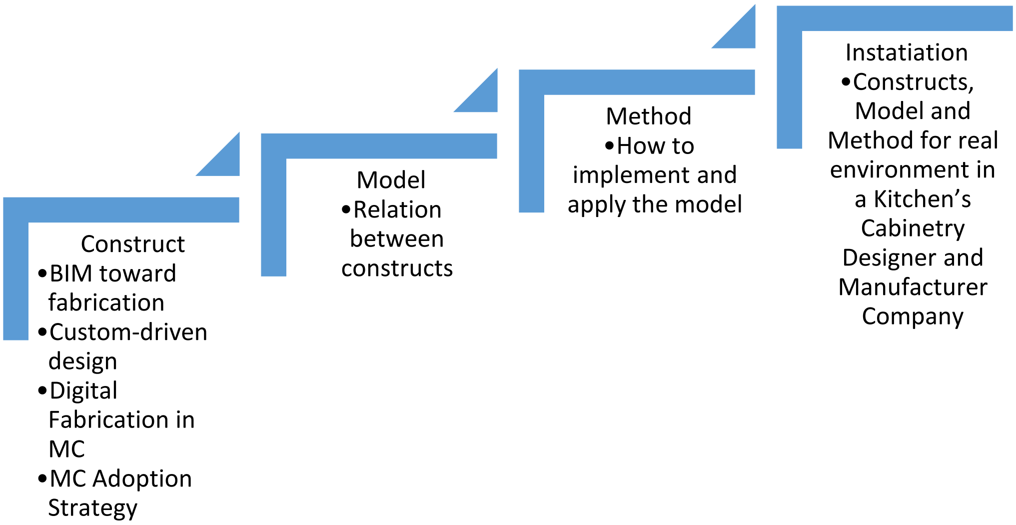
Design and construction engineering are symmetrical, differing only in emphasis, and engineering is a continuum with elements of design and construction throughout the project's lifecycle; therefore, in order to incorporate BIM into automated engineered-to-order building component, a database schema is seminal (LUTH2011). In the opinion of Luth, the current IFC-based interoperability is jammed with graphical representations of database objects, and there is a need for what he has called "*Fourth Generation Computer Technologies*", which is <u>a simplified method for the database of the building</u>. Luth continues saying that graphical user interface can be tailored to suit individual database users and remain the domain of software vendors, but "*if the database follows a universal standard for schema and content, there is no need for interoperability - everyone operates on the same database".*

Hence, a model is proposed using the concept of "engineering continuum" developed by Luth (2011). The proposed model to incorporate BIM into automated engineered-to-order building component also puts together elements presented by Goulding, Rahimian, and Wang (2014), Khalili and Chua (2013), Machado (2005), Rocha (2011), Schneider (2014), Anil, Unal, and Kurc (2012), Chen, Reichard, and Beliveau (2010) and Lee et al. (2014). Besides that, a method is suggested as a set of steps necessary to perform tasks related to automated BIM for ETO. This method has the influence of Gattas and You (2016), Eastman et al. (2010), Nawari (2012) and Venugopal (2011). The proposed model and method are operationalized by instantiation at an interior design subcontractor and fabricator. Those proposed artifacts contain data related to and description of the manufacturing process on engineered-to-order components production. The operationalization of the proposed method was performed using worldwide used programming languages and database applied in the web environment, and worldwide used BIM tools.

According to Khalili and Kolarevic (2016), true customization requires the participation of customers in the design stage, and this strategy is the highest level of customized manufacturing in the opinion of Lampel and Mintzberg (1996) who also classify it as Pure Customization. Twelve out of the fifteen companies that Machado (2005) studied, offer the participation of the clients in the design process. But the customization that these studies offer is mainly related to the choice of some options within standard designs. In these studies, companies avoid deep customer interventions in the design phase, because it requires an intense economic feasibility analysis. Therefore, in those companies, the participation of the clients in the design stage of manufacturing can be classified as an engineered-to-order type of manufacturing, but not Mass Customization at the Pure Customization level. The reason according to Farr, Poorang, and Robinson (2014) is that Mass Customization denotes an offering that meets the demands of each custumer but can be produced with the Mass Production efficiency, low-cost and high volume. According to the studies developed by Farr, Piroozfar, and Robinson (2014) and Khalili and Kolarevic (2016) the participation of clients in the design stage in the housing industry is a challenge because it requires the balance achieved between two desirable, but incompatible, features: the freedom given by parametrization and the constraint required by code compliance from regulatory bodies of the construction industry and constraints required from fabrication processes. In the opinion of Schneider (2014), the design of a product family is a difficult task, but it is a key concept of Mass Customization.

Four artifacts are idealized in this research and are related to each other as shown in Figure 52. The **Construct**-type artifacts are the conceptualizations of BIM Toward Fabrication, Custom-Driven design, Digital Fabrication in MC, and MC Adoption Strategy. The **Model-type** is a set of statements expressing the relationships among constructs. The Proposed Model demonstrates how Mass Customization can be achieved through the influence of the application of those concepts. It is the description of how those concepts can be used as tools in a Mass Customization manufacturing system. The **Method-type** is a set of steps required to perform the tasks necessary in order to make effective and tangible the relationship among the concepts proposed in the Model. BIM, Digital Fabrication, and Customization are **constructs** of the model that are integrated into steps in the method. The **Instantiation-type** proposed is the operationalization of the three artifacts described above. It is a set of rules predetermined in seeking to demonstrate the feasibility of the Constructs, the Model and the Method in a real environment in a Kitchen's Cabinetry Designer and Manufacturer Company.

Figure 52 - Artifacts proposed and developed in this Research



Source: Adapted from Dresch *et al.* (2015).

6.1. Constructs proposition

The main conceptual elements of the Model artifact proposed in this study are Custom-Driven Design, MC Adoption Strategy, BIM Toward Fabrication, and Digital Fabrication in MC.

Custom-driven Design is customer participation in the design process. In this concept, the client or the building contractor has an active role in the design process. The client even has permission to access a project database. He is granted permission to modify parameterized components available from a catalog in order to help to define the design specifications of the product. Custom-driven design includes a Web-based Elicitation, a mechanism for interaction with the client, based on a Web Database Application. In the opinion of Farr, Piroozfar, and Robinson (2014), a web database application along with BIM tools can be expected to facilitate the design process in the Mass Customization strategy. A Web-based Elicitation can help the design specialists to cross the boundaries in their traditional roles, integrating the stratified disciplines in the AEC industry.

At the core of the concept of **MC Adoption Strategy,** is the definition of which attributes of a product can be customized, the definition of which part of a product should be handcrafted and which part of the same product can be digitally fabricated. MC Adoption Strategy relies also on some other concepts. The concept of Management Toward Collaboration, Responsible Freedom, and Small Production Cells.

Management Toward Collaboration aims at minimizing the issues in the design and production of buildings and its components. Those issues, in the opinion of Kieran and Timberlake (2004), are related to the stratification of the disciplines as shown in Figure 6. Farr, Piroozfar, and Robinson (2014) say that Mass Customization has not been fully implemented in the AEC industry due to the fragmented nature of the relationship among stakeholders in this sector. Luth (2011) says that the replacement of the master-builder[23], who was an architect, engineer, and constructor, with stratified disciplines, has been disruptive to the quality in the AEC industry. Luth says that this fragmentation on the AEC industry makes the interoperability among design tools very complex. A management system toward Collaboration may bring back to the AEC industry, the quality and the whole environment from the Master-Builder's time. In a collaborative environment, engineers, architects, and fabricators would emphasize the same aspects, enhancing the collective knowledge.

Responsible Freedom is a corporate policy that gives the employees more power in the management system and at the same time requires from them commitment in regard to fulfilling the customer's needs. The importance of this approach toward implementing Mass Customization can be exemplified by the fact that the typical employee's role in a Mass Production system in which each employee is highly specialized in only one specific role, can't be applied in a Mass Customization environment due to the naturally irregular nature of its production workflow. According to Semler (1993), a management system that encourages the employees to practice role rotation prepares more than one person to execute each and every task of a job. Based on this premise, it can be reasoned that role rotation is useful to reduce the bottlenecks that otherwise would be very high in a Mass Customization production flow. But Semler asserts that role rotation is a disrupting,

[23] From the ancient time of the construction of the pyramids up to the 20th century, the architects played important role both in design and in construction and were called Master Builders. The Master Builders shared responsibilities both for the design and construction of all kinds of structures and buildings.

unsettling policy to the overall organization. Therefore, it must be within a broader management system that grants freedom but requires accountability from each employee regarding his/ her decision.

Small Production Cell means that for a Mass Customization strategy to take effect in the Small-and-Medium-Enterprise class of manufacturing companies, the functional organization of the staff should be in sets of some small groups of experts that can conduct a product in its entire production cycle. Each Small Production Cell should have the expertise to act independently and fully, from the design, going through fabrication up to the final assembly of the product on the client's site.

According to Said (2015), prefabrication is a construction approach that transfers some work from a project to a controlled external installation to be performed efficiently. Said has developed a set of data-driven prefabrication best practices, identifying opportunities for improvement in lean principles. Small Production Cell is a concept that is part of Lean principles.

The concept of **BIM toward Fabrication** encompasses the creation of BIM models aiming at the off-site fabrication, assembly and onsite installation of building components. The concept of using BIM tools toward fabrication is directed to be applied to the engineered-to-order manufacturing system, which is a system typical of small and medium-sized companies, as stated by Swierczek and Kisperska-Moron (2016). This system delivers highly customized products. According to Eastman et al. (2008), subcontractors and fabricators of components of buildings is a subgroup of the AEC industry that may benefit from BIM more than any other subgroup in the building construction industry. But as identified in the Systematic Literature Review performed in this research, subcontractors, and fabricators are yet to benefit from BIM. Therefore, this concept is directed to those aspects of BIM technology more focused on manufacturing.

Digital Fabrication is the manufacturing process of a product, in which the machines are automatically controlled by computers. The concept of Digital Fabrication in MC means that a Mass Customization manufacturing strategy focuses on the Digital Fabrication aspects that are more significant in a customization context than in a mass production environment. Digital Fabrication machines are called CNC, which means, Computer Numerical Control. In the woodworking industry, the CNC machines perform basically, drillings, lathings, and borings. Iwamoto (2009) considers Digital Fabrication as part of the broader concept of CAD/CAM and defines it as the use of digital data to control a fabrication process. Iwamoto groups Digital Fabrication techniques into five types: Sectioning, Tessellating, Folding, Contouring, and Forming. Sectioning is to cut a solid into plans and sections through orthographic projections, Tessellating is to collect pieces that fit together without gaps to form a plane or surface, Folding turns a flat surface into a three-dimensional one. Contouring is a subtractive process of creating a three-dimensional object by removing successive layers of material from a surface. Forming is to generate multiple parts from a small number of molds or forms. Folding and Contouring are the types of Digital Fabrication techniques explored in this research. Digital Fabrication has been the central component in many manufacturing industries, such as the automotive, shipbuilding, and aerospace industry. The contemporary architecture is already experimenting with Digital Fabrication in order to broaden the traditional boundaries of forms and construction processes.

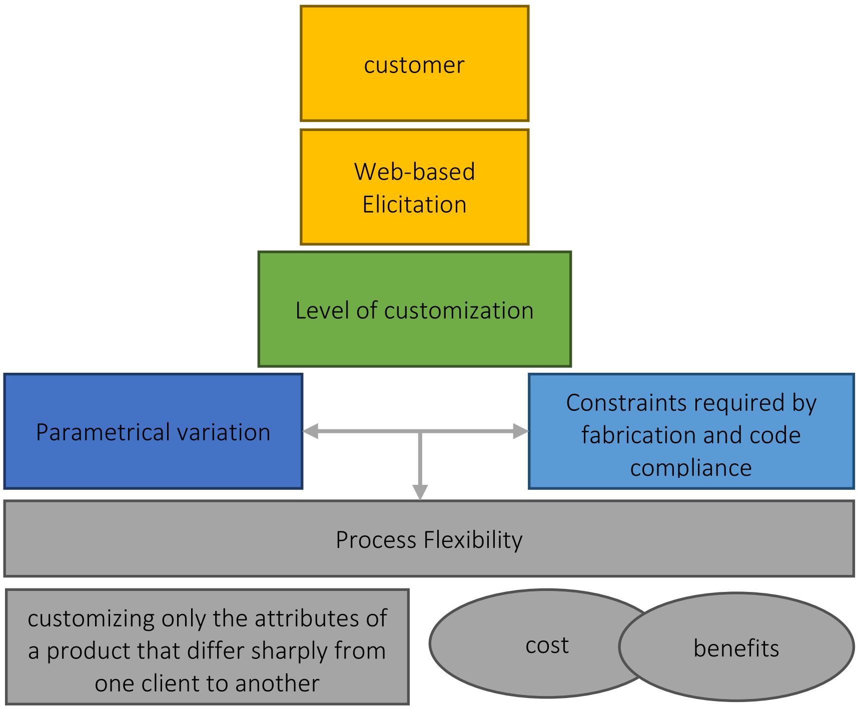
The aspects of Digital Fabrication related to the quality of the final product are more important to clients than the aspects related to production flow and speed. Special attention also is given to the Digital Fabrication aspects that are linked to customer participation in the design process of a building component.

CNC milling machines are reviving the use of Digital Fabrication in architecture. CNC machines are grouped into the two-and-a-half axis, three-axis, and five-axis, according to the number of degrees of movement that the machine can translate and the tool can rotate in order to perform the milling. The greater the number of degrees of movement a machine can offer, the more inventive an architect can be, but the fabrication process becomes more complex and expensive. The most commonly used CNC machines in the woodworking industry are the two-and-a-half axis machine. In the proposed model, the digital manufacturing application in Mass Customization should use the simplest machine possible, with the degree of complexity just enough to meet the production requirements of each product. The reason for this recommendation lies in the fact that there must be a balance between the availability of production resources on the one hand and the complexity and cost of the process on the other.

Approaches that serve as a vehicle for the interaction between the constructs presented above point to the relation between them, therefore, draw a possible model. The interaction approaches can be Web-Based Elicitation, Process Flexibility, Logistics for MC, Program Info, Component Library LOD200, Component Library LOD400, Component Parts Library LOD400, and Component As-Built Library. Web-Based Elicitation, Process Flexibility, and Logistics for MC are derived from concepts of Zipkin (2001).

Web-Based Elicitation is the mechanism for interaction with the customer through the Web, obtaining specific, intelligent information for the design. A well-designed mechanism for interaction that leads the customers in identifying exactly what they want. The level of customization achieved relies on the efficiency of the Elicitation, which according to Khalili and Kolarevic (2016) must keep the balance between the parametrical variation needed in customization with the constraints required by fabrication and code compliance from regulatory bodies of the construction industry and constraints from the fabrication process. Process Flexibility is necessary for a smooth translation between design and fabrication. This is not an easy task in a Mass Customization environment because the necessary technology evolves slowly and requires continuous development. Process Flexibility can be achieved by customizing only the attributes of a product that differ sharply from one client to another, and by paying close attention to the relation between costs and benefits of the customization of each attribute to determine its feasibility. The interaction between theses concepts is represented in Figure 53.

Figure 53 – Interaction between involved concepts for MC



Source: The author.

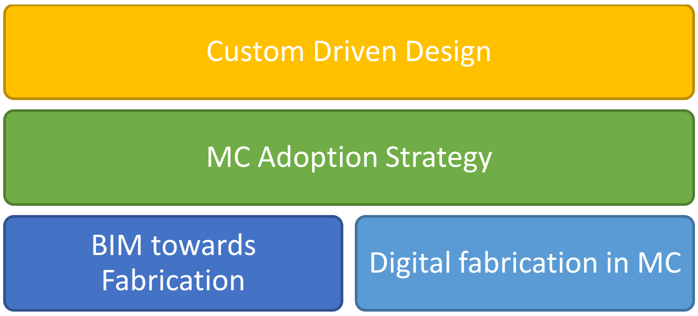
Logistics for MC encompasses the fabrication processes but gives special attention to post-fabrication processes, which in the custom kitchen and cabinetry industry, are the delivery and installation of cabinetry, accessories, and appliances on the client's specified site. In the artifacts proposed, this Mass Customization element is achieved by an identification system that enables not only the control of the production workflow but also the delivery of each component to the right client. This identification system comprises a set of information that moves along with every single piece throughout all sequence of production. The delivery of Mass Customized products in most cases are better off if performed by specialized companies.

Owing to the fact that this research aims at developing a model and a method for the implementation of Mass Customization, the researcher took into consideration the statements of Zipkin (2001), who points out that Mass Customization Manufacturing strategy should be approached cautiously because it tries to achieve two desirable but incompatible features: on one side the ability to meet the demand of each customer that comes from customization at a handcraft environment and on the other side the desire of manufacturers to achieve the efficiency, low-cost and high volume of production that comes from the standardization at the mass production environment. Zipkin noticed four limits and cautions related to the implementation of Mass Customization manufacturing strategy, and they are: (1) there is a need for a flexible production system. The required flexibility in the production system is covered by the use of BIM tools in connection with the CNC machines. (2) Efficient interaction with the clients. The need for an efficient system for interaction with the clients is met by a Web-based Database Application developed using worldwide adopted language and database. (3) A well-planned logistics for delivering a customized product. In regard to the requirement of a well-defined system to deliver the right product to the right client at the right time, the solution proposed for the woodworking industry is to hire companies specialized in delivery services. Those companies are mostly small and medium-sized enterprise (SME) and do not have the resources and logistics necessary for delivery themselves their products. (4) a clear definition of which attributes of the product can be offered customization of. This requirement is fulfilled in the Mass Customization Adoption Strategy of the proposed model.

6.2. Model Proposition

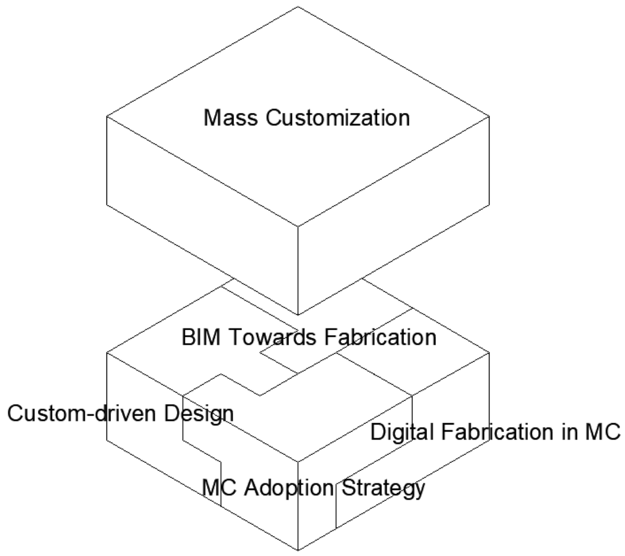
Considering the diagram of concept interactions for MC presented in Figure 53, a hierarchical model to incorporate BIM into automated engineered-to-order building component can be drawn between the constructs of Custom-driven Design, MC Adoption Strategy, BIM toward Fabrication and Digital Fabrication in MC depicted in Figure 54. However, such hierarchy simplifies a much closely linked and intertwined to form the foundation of a Mass Customization environment explored in Figure 55.

Figure 54 Mass Customization Model proposed



Source: The author.

Figure 55 - Complex and interdependent relationship among constructs in the proposed Model



Source: The author.

The three-dimensional symbolism of a well-interconnected group of puzzle-like blocks under a solid block shown in Figure 55 represents that these constructs are interlaced and that they are the foundation of Mass Customization in the proposed model. It follows the idea of Kieran and Timberlake (2004) which stated that production becomes part of the design if fabricators get involved at the beginning of the design, and design becomes part of production if designers think about how things are made and assembled. According to Kieran and Timberlake designers and fabricators must be members of a team.

BIM enables new workflow between design and fabrication processes and new interactions with clients. The Mass Customization Adoption Strategy requires a full commitment from the staff not only in terms of willingness for training but also in leaving the comfort zone in their design and fabrication practices. A Custom-driven Design relies on the adoption of BIM tools in order to make more effective the communication of design intentions between designer and client and rely also on a Web-based database application to make it possible a coherent mechanism for interaction with customers and lead them in identifying exactly what they want and setting up the design parameters. The four intercepting concepts that according to this model are necessary to implement the Mass Customization strategy in a small and medium-sized company environment. Management toward Collaboration, Responsible Freedom and Small Production Cell are concepts which are part of the

MC Adoption Strategy but are also closely linked to the Custom Driven Design and Digital Fabrication in MC concepts.

6.2.1. Custom-Driven Design

Within the context of a Custom-Driven Design, the components from the Schematic BIM Library are used for sketches and communication with clients. Communication with clients is a stepping-stone in a Mass Customization strategy according to Zipkin (2001) and is dealt with in this model through a Web-based Elicitation. Once the Schematic Design is locked down and the contract is signed, the Production BIM Library starts to be used. There is a direct action of clients in the design process by providing data through the web as well as by analyzing the BIM models.

Another point taken into consideration in the proposed model is that it allows the manufacturing of customized furniture in a sustainable environment. The project can be executed close to the customer, and the manufacturing close to materials and labor. In this case, transportation is rationalized, as it is reduced to the prefabricated product to be installed on the customer's site.

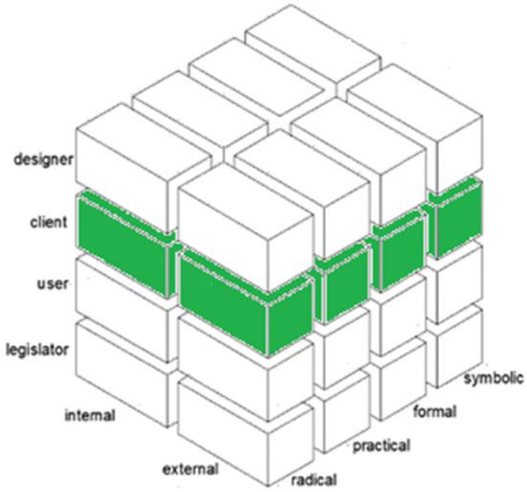
Efficient interaction with clients is a driving factor prescribed by Zipkin (2001) for the success of an MC implantation. This system must explicitly identify the attributes of the product that can be customized and must be operationalized by the principle of delaying differentiation, i.e., the point where the product becomes unique. The ability to provide effective communication with customers is also pointed out by Eastman et al. (2008) as a requirement for a BIM system dedicated to a manufacturer of building components.

The development of modeling technologies, the concerns about climate changes, and the economic pressures are some drivers of the increasing integration of design and fabrication with the involvement of clients. Instead of developing a single solution to a problem, designers can explore several parametrically designed options. Parametrics has become a way to explore relationships among objects. But designers must dedicate themselves to the practice of using the tools and to think more mathematically. Parametric design is a precondition to Custom-drive Design and geometry is the foundation of the parametric design. Woodbury (2010) says that good expertise in geometry is required in order to a designer be able to express his models, particularly in parametric design. A part of the artistic side of the designer must give way to more characteristics of a computer programmer.

According to Woodbury (2010), the design is planning and implementing changes in the world. Computers can do many of the activities of design, but not everyone. They are simply tools for design, but in order to be a skilled professional, a designer needs to have a knowledge of parametric systems, projective geometry and computer programming, or at least the basic knowledge of algorithms. Mastering those three would require from a designer to be also a mathematician and a computer scientist. Since it is hard to be an expert in one of these areas, it is crucial that the design should be practiced in a group of specialists. This is one of the relations between the concepts of Custom-driven Design and the MC Adoptions Strategy.

Design problems are established over constraints. For example, the client may express a wish for two fridges. According to the model of design problems created by Lawson (2006), clients are one out of four stakeholders that generate constraints. As illustrated in Figure 56, the constraints generated by clients are grouped by Lawson as internal and external to the problem. External constraints connect the object that is being designed to its contexts, like material, schedule or transportation. Internal constraints are inner parts of the problem. They are easier to be expressed by clients than external constraints. Internal constraints are also more flexible than the external. According to the design model of Lawson, the constraints generated by clients can be also grouped as radical, practical, formal and symbolic. The radical constraint deals with the basic roles of the designed object, Practical constraints deal with manufacturing and with the performance of the object during its lifecycle, Formal constraints are related to the visual aspects of the object, and Symbolic constraints address the abstracts properties of the object. Clients usually are the stakeholders who generate most of the radical constraints.

Figure 56 - A model of design problems from the client perspective



Source: Adapted from Lawson (2006).

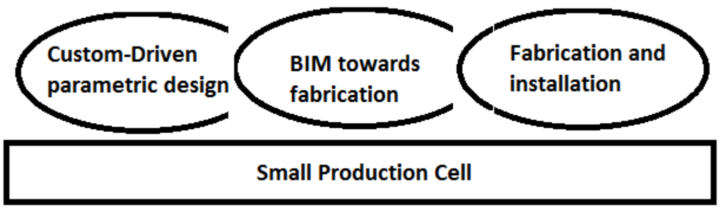
6.2.2. MC Adoption Strategy

Lawson (2006) states that Production has to become part of the design as fabricators get involved at the beginning of the process. The design has to become part of the production as designers think about how things are made and assembled. Designers and fabricators must be members of a team. Kieran and Timberlake (2004) stated that architecture specialists need to cross their traditional roles' boundaries. The MC Adoption Strategy applies these principles through the Small Production Cell illustrated in Figure 57 and Figure 61. The concept of Small Production Cell is a group of at least two specialists, one in design and one in manufacturing using BIM and database applications as links to stick together custom-driven design and digital fabrication. Small Production Cells addresses some of the limits and cautions of Mass Customization pointed by Zipkin (2001). Through Small Production Cells the production system becomes more flexible, interaction with clients are more efficient, and the transition from Sequential Engineering toward Concurrent Engineering becomes feasible.

The principle that parametric design should be practiced in a group of specialists is also endorsed by Woodbury (2010). The goal behind the creation of Small Production Cells is to have an environment that helps specialists to cross their traditional roles' boundaries. Each cell has at least three specialists. One skilled in Schematic Design, one skilled in Production design and one skilled in Fabrication.

For example, the Schematic Design could be a specialist involved with comfort, ventilation, acoustics, and other architectural aspects of the design. The Production designer could be a specialist involved with details of manufacturing, materials, definition of which parts of the product are digitally fabricated and which parts are handcrafted. The Fabrication specialist could be involved with programming and operation of the CNC machines and with the handcrafted production of some parts of the product. As part of the concept of Small Production Cell, is the practice of rotation of roles, because each specialist must have an overview of the entire process from the pampering clients in the beginning, to the small touch-ups in the final assembly. Designers should spend time doing tasks on the shop floor and fabricators should spend time learning how to make a design. This activity enhances collective intelligence and resembles the Master-builder's activity at the time of the Renaissance. Also as part of the concept of Small Production Cell, each cell takes the entire responsibility for a job, from design to fabrication and onsite installation. A cell first develops a custom-driven parametric design, performing evaluation, analysis, and synthesis of the problem according to the design model of Lawson (2006). After a solution is proposed, the cell creates BIM models with engineered-to-order fabrication parameters.

Figure 57- Small Production Cell



Source: The author.

The application of the concepts of Management Toward Collaboration promotes a Responsible Freedom and can help to strengthen the Small Production Cells. Management Toward Collaboration and Responsible Freedom follow the concept of Semler (1993), according to which management with a focus on sharing responsibilities and benefits generates collaboration. Within participatory management, employees act daily in a results-oriented manner and share both the profits and losses of the company. In an environment in which responsibilities are shared, accountable freedom is therefore developed, and reciprocal trust is generated. Management Toward Collaboration makes it easy to clearly define which attributes of a product can be customized. A clear definition of the customizable attributes is a caution that must be taken, according to Zipkin (2001), with respect to Mass Customization.

Small Production Cells is also in line with the opinion of Eastman et al. (2008). They said that BIM has a strong impact on people and requires an adoption strategy that goes beyond software, hardware, and staff training. A strategy that considers long-term actions on business and personnel in order to ensure the commitment of the staff and the assigning of the right person to each new role.

A Management Toward Collaboration is useful in addressing one of the cautiousness pointed out by Zipkin (2001) with respect to Mass Customization. Zipkin said that for Mass customization to deliver real value, the attributes that make a product unique must be the ones whose preferences differ sharply from one client to another and that costs and benefits should be analyzed carefully.

Within the context of a Small Production Cell, it is easier to address also the concept of Parvez (2018) according to which designers still need to master the fundamental concepts of geometry.

6.2.3. BIM Toward Fabrication

The concept of BIM Toward Fabrication blends BIM implementation concepts of Eastman (2008) with Flexible Production within Mass Customization concepts of Zipkin (2001). Eastman prescribed four steps for BIM implementation: setting goals, defining adoptions activities, establishing the pace of changes, and setting human resources strategy. The main goal is to create a flexible production environment. The adoption activities are related to the creation of two libraries of product components, one intended to be used at the custom-driven design, and the other intended to be used at the Digital Fabrication. The adoption activities also consider the limits and cautions prescribed and emphasized by Zipkin (2001), in relation to the process of adoption of Mass Customization. The establishment of the pace of changes and setting human resources strategy are related to the concept of MC Adoption Strategy. The establishment of the pace of changes must be determined dynamically in the BIM implementation as the Participatory Management evolves. The activities related to setting human resources strategy are the definition of the responsibilities of the BIM Manager, as well as the responsibilities of each member of a Small Production Cell. The concept of Small Production Cell is shown in Figure 57. The rotation of roles among members of the Small Production Cell is used for the purpose of training as part of the strategy related to human resources. Some of the actions prescribed by Semler (1993) may be useful to develop a collaborative process through the application of the principle of responsible freedom implemented according to the reality of each company.

Two distinct libraries of three-dimensional BIM models are envisioned. The first library, called Schematic BIM Library, contains components for the Schematic Design phase. Components have approximate sizes and locations. Schematic parameter values are imported from a web database application. The second library, called Production BIM Library contains components for the phase of Design Development and Documents for Fabrication. Components have precise sizes and locations. Parameter values for details and documents for fabrication are imported from a web database application. Modularity allows the operationalization of the principle of variety through recombination of parts.

Within a strategy of Mass Customization, the BIM Manager, besides managing the library of components, has an additional role. At the beginning of the BIM implementation process, he must create a library with every component that the designers need in order to create the Schematic Design and the Fabrication details design. As soon as a Small Production Cell is stabilized, the BIM Manager starts to teach the specialists in that cell to create the components they need. From that moment on, the main role of the BIM Manager regarding that cell is to provide technical support to the specialists in creating the components for the libraries.

Parametric modeling has allowed designers to make a complex design with precise connections between components which are controlled through numerical, textual or logic parameters. This great benefit already achieved in design processes has given the designers more freedom to discover new ideas and opportunity for great innovations. Nevertheless, Woodbury (2010) says that the processes of fabrication still are some of the constraints and limitations in transforming a virtual model into a real object or a component for a building. Therefore, the use of BIM tools prescribed in the proposed model is focused toward direct benefits to Digital fabrication.

Almost all professionals who use parametric modeling are interested in having skills in the area of software programming but lack formal education in it. This is the characteristics of the professionals who write many programs used in the woodworking industry. Nevertheless, almost all programming tools are designed by computer specialists with a high sense of abstraction, and skilled in data structures, which makes those tools very complex for a non-computer-specialist, like most of the designers. Woodbury (2010) shows some simplified techniques and pattern ideas which may help the designer to achieve their programming tasks, especially those who according to the model developed in this research, perform the role of BIM Managers toward the creation of libraries of components for digital fabrication.

The Mass Customization method derived from this model makes use of spreadsheets with BIM tools toward digital fabrication, and this is in tune with the concepts of Woodbury (2010), whereby spreadsheets are widely used parametric tools. But special attention must be given by the designer in order to avoid the creation of cyclic graphs with infinite loops. The use of BIM tools in modeling families in the environment of Mass Customization should make use of two techniques suggested by Woodbury (2010), which are geometric constructions and programming. Geometric constructions that require the skills of projective geometry, and programming that requires skills to build a model writing algorithm. Special efforts must be done in order to embed the problem constraints into the web database application and import them into the model parameters. Those constraints must be expressed before the creation of the models. According to the concepts of Woodboury (2010), independently of the tool used, whether a spreadsheet, a web database application, or a BIM tool, the expression of those constraints must be simple, clear and reliable.

6.2.4. Digital Fabrication in MC

Mass Customization tends to be a strategy adopted typically by Small and Medium Manufacturers because it requires that some items be handcrafted while others can be manufactured digitally. The concept of Digital fabrication in MC is mainly related to finding and keeping a balance between handcrafted fabrication and Digital fabrication, in order to achieve the Flexible production prescribed by Zipkin (2001). The efficiency of a Mass Customization strategy depends on the proper definition of which parts of a product are to be handcrafted and which parts are to be produced through Digital Fabrication.

Iwamoto (2009) groups Digital Fabrication techniques into five types: Sectioning, Tessellating, Folding, Contouring, and Forming. Kieran and Timberlake (2004) stated that the aircraft, automotive, and shipbuilding industries are based on modules. Modularization is the strategy adopted for Digital Fabrication in this proposed model. It is performed basically through two techniques. Folding and Contouring were the techniques selected to be used in this model in the environment of a woodworking cabinetry industry. Figure 58 and Figure 59 shows examples of Folding which is to turn a flat surface into a three-dimensional one. Folding can be used in the design of fascias and valances for digital fabrication of woodworking cabinetry. Figure 60 shows an example of Contouring which is a subtractive process of creating a three-dimensional object by removing successive layers of material from a surface. Contouring can be used in the design of doors, drawer fronts, moldings and panels for digital fabrication of kitchens.

Figure 58 – Folding by mitred-cut as a digital fabrication technique

Source: The author.

Figure 59 - Folding by straight-cut as a digital fabrication technique

Source: The author.

Figure 60 - Contouring as a digital fabrication technique

Source: The author.

Object-Oriented Programming (OOP) is a logical concept largely used in computer programming. The OOP concept is embedded in the creation of BIM models, and must also be in the Digital Fabrication within the strategy of Mass Customization. Documents for fabrication are generated following OOP concepts such as Classes, Encapsulation, and Inheritance.

The Small Production Cell described in the MC adoption strategy operationalize the principle of rapid adjustment of the production in terms of the capacity of production, the functionality of processes, fabrication structure, and production control.

Due to the inherent variability in the production of customized products, the logistics for production can not have a flow similar to mass production because the result is bottlenecks in the production.

Although modularization is already being used in Mass Production in several industries, Newman et. al. (2014) and Leon et.al. (2013) identified some challenges in the implementation of modularization in customized products. According to Newman, interoperability between the CNC machines and the computers used for design is a major issue in the manufacturing industry, which still requires research and development. And Leon reported that CNC machines require considerable efforts and expertise in the setup and programming process, before bringing the machine into production. Those challenges can be faced in a first instance by performing interoperability between CNC machines and the computers used for design through text files.

According to Zipkin (2001), Mass customization has some limits and should be approached cautiously. It requires a well-defined system to deliver the right product to the right client at the right time. A very useful resource in Digital

Fabrication in MC, to facilitate this process is the use of a system of labels that are attached in each piece allowing the identification of each one at each stage of production.

6.3. Method Proposition

As it was with the proposed Model, the Mass customization proposed method also took into consideration the limits and cautiousness pointed by Zipkin (2001), thati is, a flexible production system, an efficient system for interaction with clients, a well-defined logistics for production and delivery, and a careful definition of which attributes of a product, can be customized. The proposed method to implement and apply the model to incorporate BIM into automated engineered-to-order building component encompasses actions that meet these cautions. Some of those actions are highlighted and summarized next. (1) Designers were encouraged to learn computer programming and received basic training in algorithms. The objective is to enable them to better utilize the resources available in parametric modeling software. (2) Special attention must be given to naming parameters. Parameter names must represent well the values they hold. (3) Each part of the product must be traceable throughout the production process. This requirement was met with a system of labels attached to the piece as it leaves the CNC machine. (4) A web database application is created to help to express in the very beginning of the design process, both, the constraints that come from the client's desires and the restrictions that come from the fabrication process. In the proposed method, the client plays an active role in the process, either through personal meetings or virtually, by feeding the Web database application.

By comparing concepts from the proposed model shown Figure 54 with tasks from the proposed method shown in Figure 61, Figure 62, and Figure 63, it can be noted that the Custom-Driven Design on the proposed model corresponds to the Validate Program Info task in the proposed method. The concept of BIM Toward Fabrication from the proposed model is related to authoring and validation of the Schematic BIM modules, and the authoring and validation of the Production BIM modules in the proposed method. The concept of Digital Fabrication in MC in the proposed model corresponds to the Generate G-Code, Fabrication and Installation of components, and authoring the as-built modules in the proposed method.

As can be seen in the overall map shown in Figure 61, the first task is the web-based elicitation which gets from the owner or the subcontractor, the Program Info. The elicitation with clients through the web database application feeds the constraints for the BIM models. Next comes the authoring process of the Schematic BIM Model and then the process of authoring the Production BIM Model which are detailed in Figure 63. Even though with an intelligent logic being embedded in the web database application, the Program Info should be validated by the design. If declared consistent, then the next step of authoring the Schematic BIM model would be performed. In its turn, the BIM Model would be validated with the Job Owner or with the subcontractor. When the architect declares that the Schematic BIM Model is valid, the engineer starts the authoring of the Production BIM Model and at last validates it with the architect. After the Production BIM Model is validated, the component is fabricated by CNC machines, assembled and installed. The last task is the Authoring of As-built modules by the engineer. Those As-built modules are saved for future component maintenance and for a possible feeding of the Component Library LOD200, the Component Library LOD400, and the Component parts Library LOD400.

As can be observed in Figure 61, there are overlaps between design and engineering, and between Engineering and production. While the designer is still in the phase of tendering the clients, the engineer can already start to create the detailed components.

Promob, a Brazilian company, and 2020, a Canadian company, have teamed up to offer technology to cabinetmakers, furniture makers, architects, interior designers, and furniture retailers. But their tools are designed to meet customer needs through small modifications made to a standardized design. Within the classification of manufacturing strategies according to Lampel and Mintzberg (1996), shown in Figure 3 and Table 1, they fall into the Tailored Customization level. The method developed in this research aims to solve the problems faced by designers and manufacturers of engineered-to-order products when the design is totally made to the customers specifications. Within the classification of manufacturing strategies according to Lampel and Mintzberg (1996), it falls into the Pure Customization level as shown in Figure 3 and Table 1.

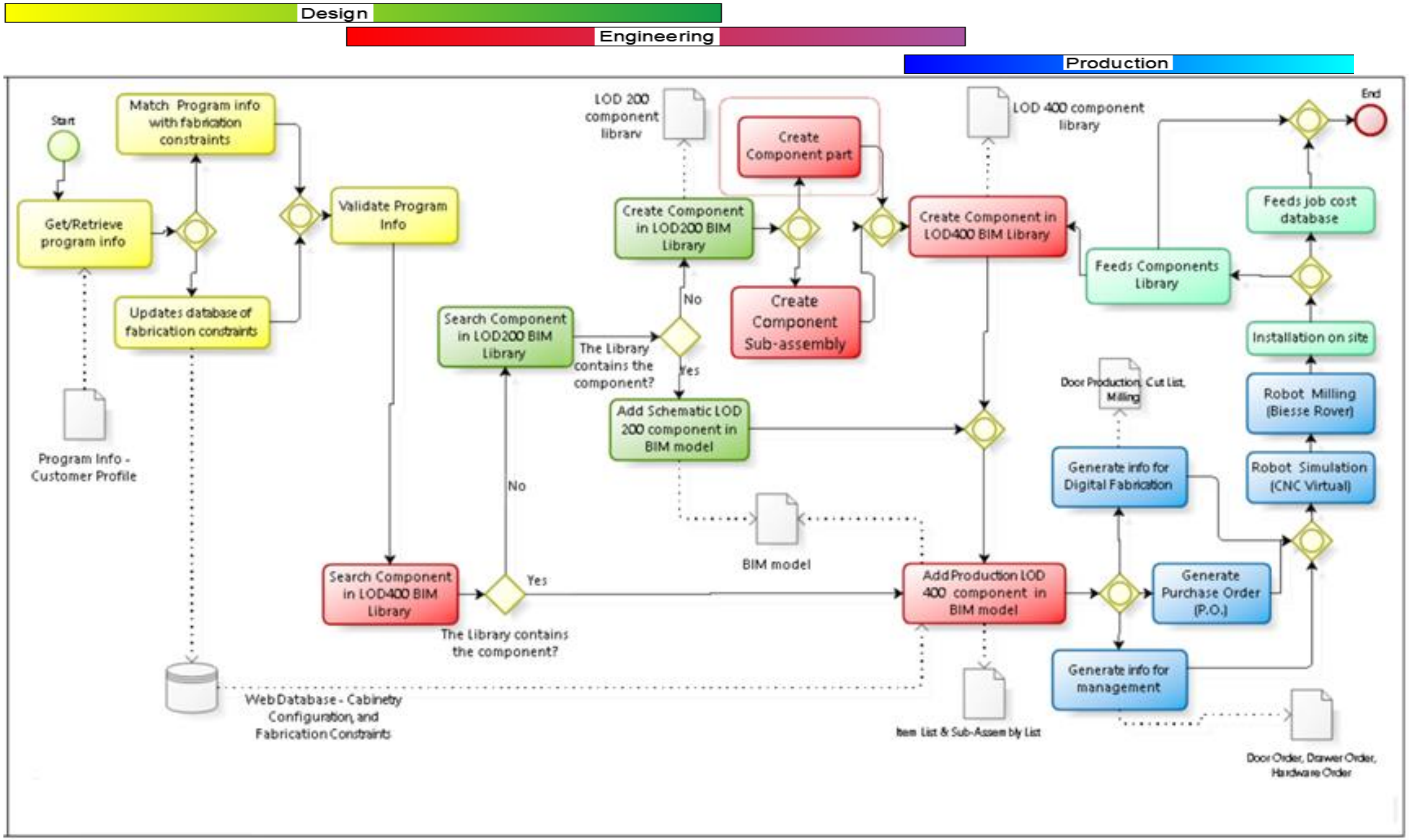
According to the proposed method, a BIM manager is responsible for giving support to staff in the Small Production Cell in the development of the Component Library LOD200 that contains the models used in the authoring of the Schematic BIM model, and the Component Library LOD400 that contains the models used in the Authoring the Production BIM model.

The process of Authoring the Schematic BIM Model shown in Figure 62, is performed by the architect/designer. His first task is to retrieve the Program Info saved previously in the database. With this information, he searches the Component Library-LOD200 for the objects needed for the modeling job. If the Library does not have all the needed objects, The BIM manager creates them in the Components Library-LOD200, and in the Components Library-LOD400 and, if necessary, in the Components Parts Library-LOD400. Then, the process flows back to the architect/designer that proceeds with the authoring of the Schematic BIM Model.

The process of Authoring the Production BIM Model detailed in Figure 63, is conducted by the fabrication specialist. His first task is to retrieve the Schematic BIM Model-LOD200 authored previously by the designer. With this model, he searches the Components Library-LOD400 for the cabinets and accessories needed for the Production BIM Model authoring. If the Library does not have all the needed components, the missing components are created in the Library LOD400, and, if necessary, parts are also created in the Component Part Library LOD400. Then, the process flows back to the fabrication specialist that proceeds with the authoring of the Production BIM Model.

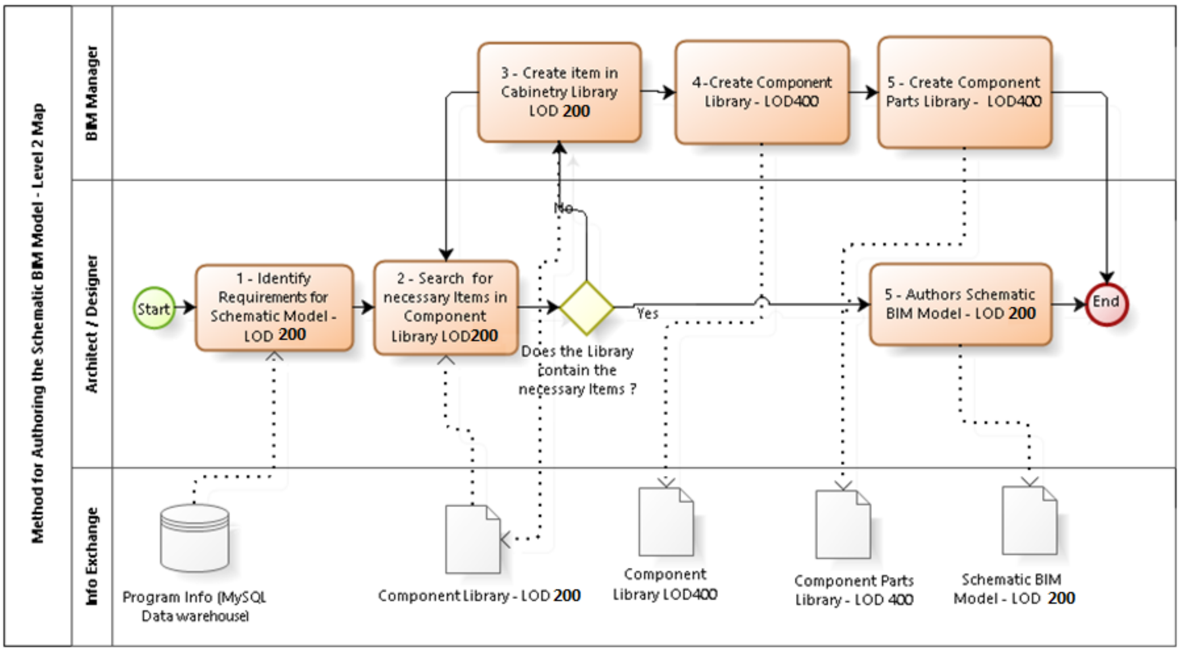
The proposed method for Digital fabrication toward Mass Customization encompasses some of the patterns designed by Woodbury (2010). The use of those patterns requires that designers first learn the basic commands of a tool and create a very simple model. Then they must break a complex body into simple components according to predefined constraints related to fabrication. Based on these constraints, a model for each component is created. Finally, the components become patterns that interact with each other toward the modeling of the original complex body.

Figure 61 - BIM mediated method for Engineered-to-order Woodworking cabinetry



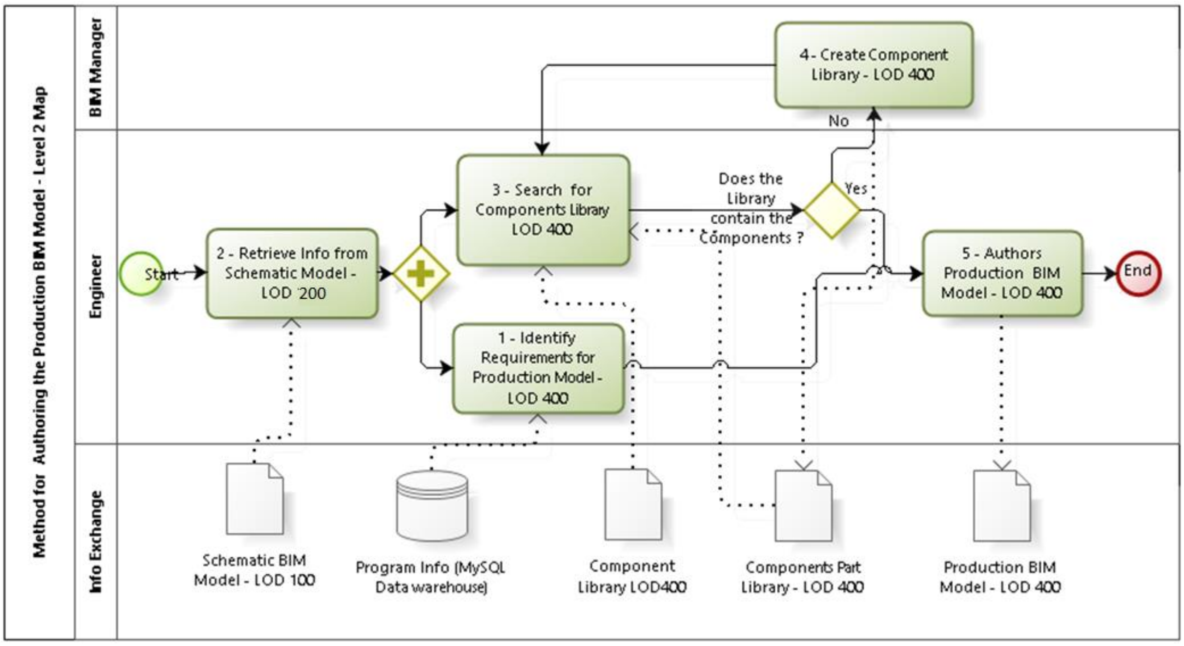
Source: The author.

Figure 62 - Method for Authoring the Schematic BIM Model – level 2 Map



Source: The author.

Figure 63 - Method for Authoring the Production BIM Model – level 2 Map



Source: The author.

The creation of the library of components for modeling, using patterns, is a collaborative work between designers, engineers, and fabricators. Patterns are easily copied, modified, and used both for the modeling in the preliminary design and for the modeling in the fabrication design. Designers are encouraged to using patterns created by others in order to develop the skills to write their own patterns. It takes more time and effort to create the library of component models using patterns, but the expected benefits are the reuse of design ideas, more clarity, simplicity, and quality in the fabrication. In order to create a pattern, designers, engineers, and fabricators must answer these questions: which are the tasks in design and fabrication that are done over and over with small variations? Can these tasks be described with short sentences?

Six patterns out of the thirteen presented by Wodbury (2010) were incorporated in the method, aiming at a parametric design toward digital fabrication. The first pattern is the *Clear Names* because they are required for every pattern and they must be names meaningful for designers and fabricators. *Controller* and *Jig* are the patterns selected from the category of techniques for structuring a model. The *Jig* pattern expresses the structure of each host family in terms of reference planes and the location of nested families. Host families are built on top of a *Jig* pattern. From the third category, *Point Collector* specify the location of each component part and the spatial relationship between them. The *Reporter* pattern was selected from the category that retrieves information from models. The generation of data sent to the CNC machines follows this pattern. Text and numeric lists are generated from geometric parts of the models. In a *Reporter* pattern, the information flows from target to source and this is what is required in design for digital fabrication. A *Reporter* extracts from the model the information that the CNC machine needs, transforming data from design into data for fabrication. Through *Mapping* patterns, simple models of components are created and combined in more complex forms. Parts are created separated with distinct sets of inputs and outputs. Then they are incorporated in the main model with different sets of inputs and outputs. The repetitive use of functions turns feasible the fabrication of complex models through the strategy of “divide-to-conquer”.

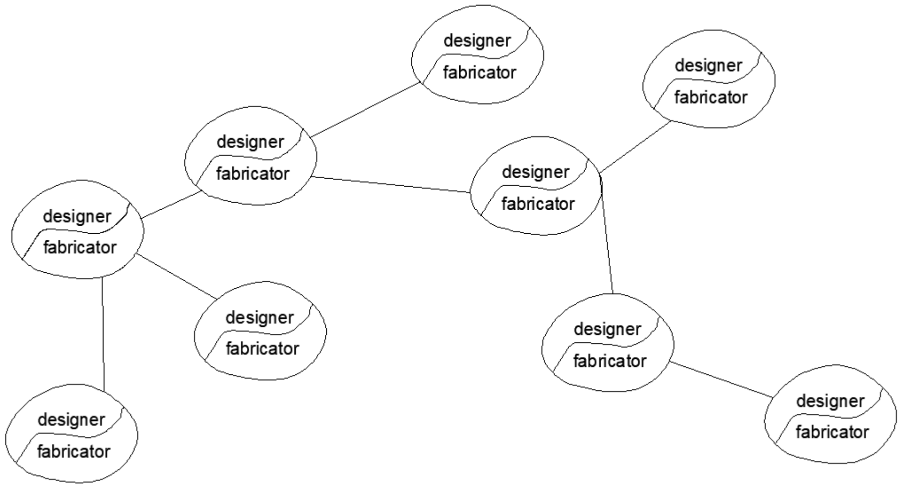
Designers need to have some knowledge of the concepts of point and vectors, which are the fundamental objects upon which the three-dimensional operations are performed. Parametric modeling tools rely on points, vectors, operations between points and vectors, operations between vectors, operations with lines in two-dimensional space, and operations with planes in three-dimensional space. The right-hand rules to define orientation and rotation are very straightforward rules to simplify the designers and fabricators job. Modern modeling tools have allowed designers to create very complex forms, but the processes of fabrication still have limitations in the transformation of a virtual model into a real object.

Parameters control the constraints, which means that a change in the design model reflects easily in the fabrication parts. Computer Programming is embedded in parametric modeling toward fabrication. Designers must have knowledge of at least the basic concepts of algorithms. The key concepts are values, variables, expressions, statements, control statements, functions, and types. Parametric modeling requires intensive use of functions in order to enable the reuse of a model. Objects, classes, and methods are more complex concepts, but very important in parametric modeling because they deal with parameters inheritance. Object is a coherent generalization of values. Class is a generalization of objects and Method is a function specific to a certain class.

The proposed method comprises the creation of Small Production Cells. One Small Production Cell is a team of specialists. As can be seen in Figure 64, each Small Production Cell must have at least two specialists, being one design specialist and one manufacturing expert. They must be able to make a complete product, not only parts. Instead of an environment in which each worker or department is responsible for creating isolated components, each Small Production Cell must be able to conduct the process of manufacturing a product from design to fabrication. The concept presented in Figure 64 is that as a Small Production Cell consolidates and the number of specialists within that Cell increases, this Cell is able to generate another Cell in the organization. In a Small Production Cell each specialist masters several roles, which reduces the bottleneck in the production flow. Bottlenecks in the production flow is a key challenge in the manufacturing of Engineered-to-order products.

Semler (1993) implemented at Semco, participative management based on principles that the company must encourage the Collaboration and the commitment of each worker. Semler, CEO at Semco, stresses that participative management is not easy, but it is worth a try. In order to do so, he replaced the traditional pyramidal management structure to a new structure of concentric circles. He went away from the traditional paternalistic management approach and adopted actions that encourage the employee’s commitment to a results-driven environment and created a profit-sharing plan in which the company establishes a percentage of its profit to distribute to its employees, and they decide in assemblies how to split it. A list of the Management Concepts toward Collaboration adopted by Semler (1993) is detailed in Appendix J. A summary of those concepts that were especially relevant in the experiment is presented in Table 23. Many of the actions proposed in this model for the adoption of Mass Customization were taken from the experience of Semler.

Figure 64 - A model for the creation of Small Production Cells



Source: The author.

Table 23 - Excerpt of the Management concepts toward Collaboration adopted by Semco

ACTION	SUMMARY
Small Production cells	Instead of assembly lines, production machines are clustered so teams of workers can assemble a complete product, not an isolated component. This gives the workers more autonomy and responsibility. They become happier and more productive. Each worker masters several different roles.
Job rotation	Employees exchanging roles is encouraged by the company. This can be disturbing but offers considerable advantages, such as acquiring new skills, provide employees with a broader view of the company's business, prepares more than a person for each role, and creates opportunities for those who feel trapped.
Profit sharing	The company negotiates with the workers the percentage that are distributed and they decide how to split it.
Participation	Employee's involvement is the backbore of the company's management system. Every voice counts and have a vote.
Satisfaction	The level of dignity of each employee must be high. He must have a sense of achievement that ensures the quality of everything that he or she does.

Source: Adapted from Semler (1993).

The Small Production Cell system adopts some of the actions implemented by Semler (1993), like the creation of a more participative environment with more committed workers in order to achieve Process Flexibility that according to Zipkin (2001) is a condition that can be a limit to the implementation of Mass

Customization and should have a cautious approach. According to Zipkin, without the Process Flexibility, the Mass Customization production system is threatened.

According to Woodbury (2010), designing requires new skills from the designers and offers them new design strategies as summarized in Figure 65. The relation between skills and design strategies is especially relevant in the Mass Customization environment. For example, the ability to remove from each module every external dependency offers the design the strategy of creating algorithms that produce a variety with a minor variation of parameters. The skill to write algorithms using parameters and constraints offers the design the strategy of encapsulating modules with independent parameters. Expertise in giving meaningful names to parameters gives the designer the means to use the strategy of creating his own set of reusable modules and functions. Competence in identifying objects and developing data flow between them gives the designer the ability to create mechanisms to postpone project decisions.

Figure 65- Skills required and Strategies available

Skills

- Identify objects and develop data flow between them
- Dividing a problem into subproblems
- Giving meaningful names to parameters
- Removing from each module every external dependency, whenever it is possible
- Writing a problem in mathematical terms
- Writing algorithms using the parameters and constraints

Strategies

- Sketching with paper and pencil
- Create computer programs just tailored without generic use concerns
- Wherever possible, to use existing codes
- Create algorithms that produce variety with minor variation of parameters
- Use mathematics
- Create mechanisms to postpone project decisions
- encapsulate modules with independent parameters
- be willing to help others
- develop the own set of reusable modules

Source: Adapted from Wodbury (2010).

As stated by Eastman et al. (2008) fabricators of components for buildings may have more to gain from BIM than any other stakeholder in the building construction process, because increasing portions of building components and systems are being pre-assembled or fabricated off-site. BIM models provide automated code for CNC machines and reduce the human labor necessary to set up the machines. As a result, shorter lead times are achieved because shop drawings are generated later in the manufacturing process, and then clients can make late changes. Parametric design with components nested according to pre-defined rules and constraints is used in the proposed model to meet the requirements of Eastman for BIM toward fabrication.

According to Shelden (2014), although the architecture is going through a deep transition, there remains an essential mismatch between the overflow of digital information and the limits on digital fabrication. The knowledge of mathematical concepts and of the concepts of objects, classes, methods, and Data structures, are skills necessary to be applied in the parameterization of BIM models and in the creation of algorithms for the web database applications. This is in tune with the opinion of Farr, Piroozfar, and Robinson (2014) and Leiner et al. (2017), that highlighted the importance of Web database applications for facilitating Mass Customization in the AEC industry.

The proposed method adapted from Woodbury (2010), a four-step sequence to create the Library of components for design and fabrication of customized products. The first step is to break a complex component into simple subcomponents. The second step is to classify the subcomponents by degree of similarity between their parameters. The third step is to group subcomponents with similar parameters creating patterns. The fourth is to create the original complex component using the patterns.

According to Lawson (2006), what was called Computer-Aided Design was actually Computer-Aided Drawing. Computers now are being used to aid the design process but the dialog between problem and solution is still not easy. Lawson says that the solution to this problem is not simple, because the software has the capability to perform a great number of functions, but large number of those functions are seldom needed, and the software became extremely complex to be understood. Designers are too busy to have time to be spent with manuals or courses. They may even notice that some functions might be helpful but only on rare occasions. Even if they have the chance to learn those features, by the time they need them, they have already forgotten how to execute them.

Parameters control geometric objects, but each BIM tool is specific to a type of task. This causes designers to be constrained by the tools they choose. And in order to choose the right tool, designers must be able to link their design intention with the mathematics of the modeling tool. However, projective geometry is the foundation of the parametric modeling and according to Pauly (2003), operations with vectors and parameters are the basis of all modeling tools. Therefore, the right-hand rule to define the orientation of the coordinate system and the right-hand rule to define the positive rotation around an axis were the basic skills that the researcher taught designers of the company.

The method prescribes the collect, storage, and processing of data using short learning curve tools. The use of web tools (HTML, CSS, PHP,) facilitates communication anywhere in the world that has internet. Furthermore, MariaDB, the database used in the research is free and is the most used open-source relational database on the web.

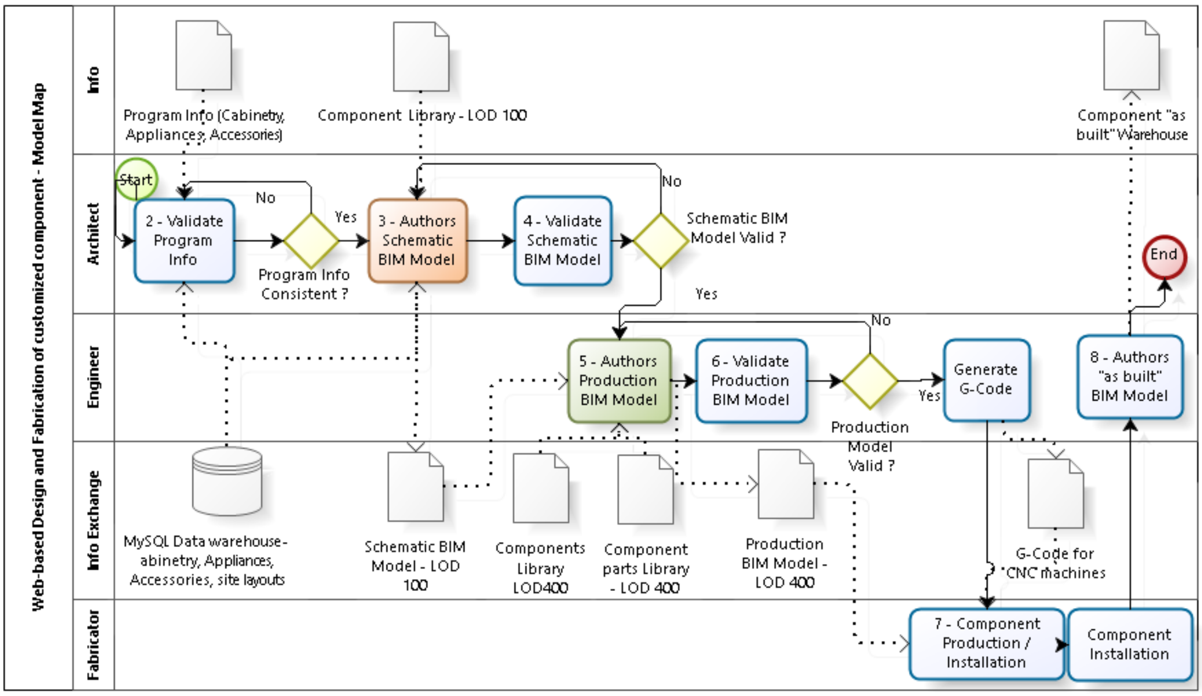
The proposed method took into account the fact that furniture manufacturers are trying to implement Mass Customization using Mass Production methods and technologies. Methods and technologies that are adequate and efficient in the context of Mass Production, may be totally ineffective and unproductive in a Mass Customization environment. The insufficiency of adapting Mass Production methods and technologies to Mass Customization can be illustrated with a well-known word from Jesus: "*do not put new wine into old wineskins, or else the wineskins break, the wine is spilled, and the wineskins are ruined*…."[24] Therefore, MC requires its own methods and technologies.

6.4. Instantiation Proposition

The objective of the Instantiation was to demonstrate the feasibility and effectiveness of the BIM mediated Mass Customization proposed model shown in Figure 54, and illustrate the complexity and interdependency among the constructs in the model shown in Figure 55. The objective of the Instantiation was also to test the proposed method shown in Figure 66 Figure 61and which must be performed in the context of Small Production Cells as shown in Figure 57 and Figure 64 which were detailed within the MC adoption Strategy concept of the model.

[24] Matthew chapter nine and verse seventeen in the Bible

Figure 66 - BIM mediated Mass Customization method



Source: The author.

The instantiation was carried out in two cycles of an action-research. The feasibility of the Custom-Drive Design, Figure 54, was conducted through a web database application designed to get specific and intelligent information for parameterization within the BIM modules. Computer programming basic concepts as in Table 3, were used not only to develop the web database application but also to create the algorithms for the parameterization of the BIM modules. In the first cycle, a simple kitchen with five cabinets was designed and fabricated using the straight-cut folding digital fabrication technique shown in Figure 59. Folding is one of five digital manufacturing techniques described by Iwamoto (2009).

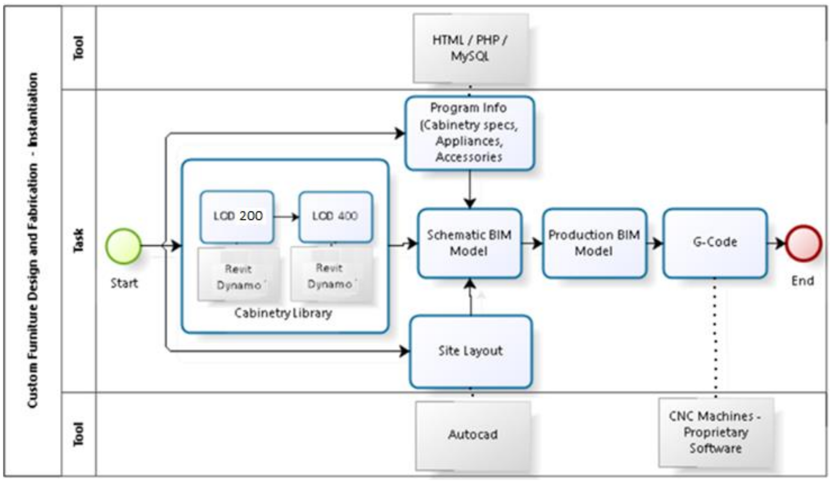
Regarding the Generate G-Code step referenced to in Figure 61 and Figure 66, modern CNC machine languages are powerful tools used to bridge the gap between the BIM modeling tools, and the G-codes that the CNC machines understand. Although CNC machine makers provide structured and user-friendly graphical interface programming environments, ultimately, these tools convert their commands to G-code. Therefore, a G-code knowledge was important to understand coordinates, feed rates and other actions in a CNC machine. Machines are different from each other. Each CNC machine has specific functions, and a unique device called Post-Processor. The Post-Processor works to make sure that the G-Code, which is generic, can provide instruction according to the specific characteristics of the machine. Every CNC machine follows a set of core functions that are common to every machine. G-Codes can be edited in any text editor. At the beginning of each program, there is a block of commands that sets the initial values desired for the machine environment. Normally they set the machine tooling, spindle, work offsets, and job sequence to its original configuration. Before running a program in a real machine, it must be run in a simulator. Submitting a program through a simulator detects errors and prevents damage to the machine

The Instantiation encompassed the development of the web-based graphical interface using in HTML and PHP languages connected to a MariaDB database. Two additional tools were selected in the development of the system. Figure 68 shows the environment of XAMPP, which was the chosen tool for Web-server and Figure 69 shows a screen from Netbeans, which was the chosen tool as the programming environment. Those tools were selected because they are the most common and worldwide adopted web tools, and they are free open-source tools. The information retrieved was transferred to the BIM models. The Schematic BIM Model and the Production BIM Model were operationalized according to the software and data structure shown in Figure 67.

Relatively to the concepts of BIM Toward Fabrication and Digital Fabrication in MC, Figure 54, the second cycle focused on more complex components with the objective of experimenting with the balance between the parametrical variation needed in customization and the constraints required by fabrication and by code compliance from regulatory bodies of the construction industry, Figure 53.

Regarding the tools selected for the Web-Based Elicitation process, Tittel and James (1997) expressed that HTML is a text-based language that provides support for information searching through a vast quantity of data scattered across computers worldwide. Although higher-level tools are widely used on the web, the backbone for World Wide Web pages is still HTML. Tittel and James (1997) stated also that PHP is a language with accessibility to MySQL, Oracle, SQL Server, Informix, and many other RDBMS databases; RDBS stands for a Relational Database Management System, that uses the Structured Query Language – SQL. MariaDB was the database used in the experiment. MariaDB was created by the same programmers who developed MySQL, led by Ulf Michael Widenius, the same programmer who led the development of the original version of MySQL. MySQL is no more a free database. MariaDB was created to remain a free and open-source database, to have the same compatibility with PHP, and it is also a worldwide used database in the web environment. All selected tools are open source, and in order to get them, one just must go to their official website. They are the perfect choice for a group of companies characterized as of little investment in technology as is the case of small and medium manufacturers of customized products.

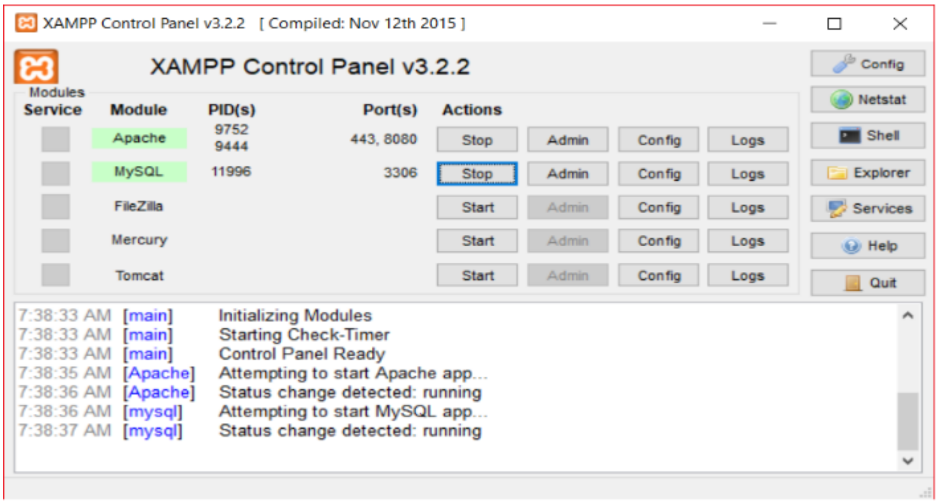
Figure 67- Custom Furniture design and fabrication – Instantiation tools



Source: The author.

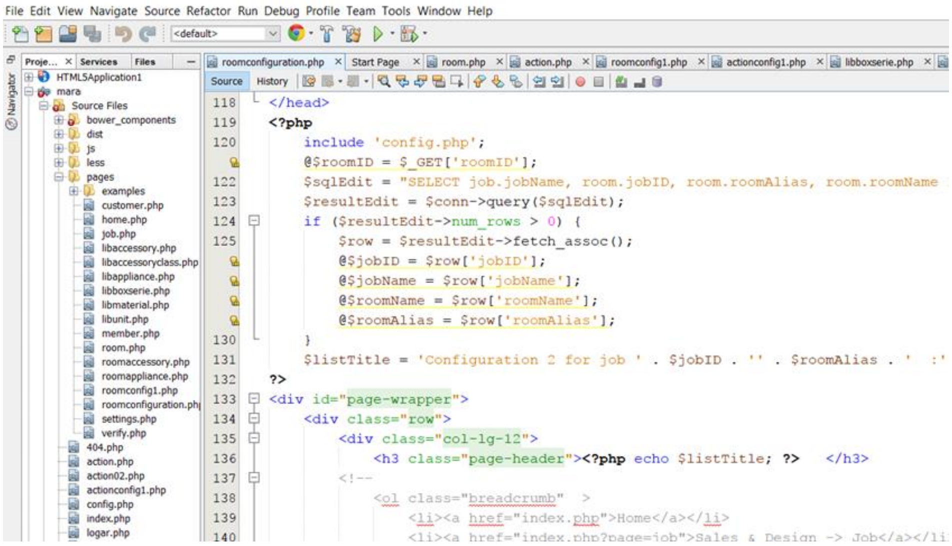
Regarding the Object-Oriented Programming tools for the development of the Component Library LOD200, the Component Library LOD400, and the Component Library Parts LOD400, the system uses a worldwide adopted database and the most adopted programming language in the web environment aiming to improve the communication of building information among disciplines and stakeholders. This open architecture software system allows the participation of the clients in the design stage of manufacturing, which can be classified as Pure Customization. It provides the integration between the Web tools and BIM and Digital Fabrication tools. The tools that were used are: (1) **HTML**, which is a text-based language that provides support for information search through a vast quantity of data scattered across computers worldwide; (2) **PHP**, which is a worldwide used language, mainly in the web environment, that provide database accessibility through web pages developed with HTML; (3) **MariaDB**, which, among all databases, is the best open-source used worldwide in the web environment. MariaDB is an RDBMS that uses the Structured Query Language – SQL. Those three tools described above are open source. (4) The chosen **modeling tools** was Autodesk REVIT and Autodesk DYNAMO. (5) As illustrated in Figure 68 and Figure 69 some additional **development tools** were used like XAMPP Control Panel V.3.2.2 and NetBeans IDE 8.1. XAMPP is a free and open-source cross-platform web server solution. It is a simple tool that makes it extremely easy for developers to create a local web server for testing and deployment purposes. It provides the set up of a web server, that is, the Apache as a server application, the MariaDB as a database and PHP as the scripting language as a cross-platform, it works on Linux, Mac, and Windows. NetBeans is a code analyzer and editor that was used for working with HTML and PHP. NetBeans IDE is a free open source that has a worldwide community of users and developers.

Figure 68 - XAMPP as the web-server solution



Source: The author.

Figure 69 - NetBeans as the code analyser and editor



Source: The author.

The choice of HTML / PHP and MariaDB as tools for the Web database application is in line with Eastman (2008) that stated that the ability to provide effective communication with stakeholders outside the fabricator's environment such as suppliers and components installers is a requirement for BIM systems at Engineered-to-order fabricators. According to Lampel and Mintzberg (1996), in a pure customization environment, a design is made to the customer specification and the collecting information on customer preferences and product specifications require simple tools so that dedicated systems may be developed efficiently. Mass Customization is a strategy predominantly practiced by Small and Medium Enterprises. This group of companies does not have many resources to invest in technology. HTML / PHP and MariaDB have a short learning curve, and MariaDB is a Relational Database Management System that uses SQL language. These tools are widely used all over the world. This facilitates the hiring process of new employees and the training of the design and manufacturing specialists becomes easier because there is plenty of learning material available on the web.

Concerning the relation between suppliers and builders, it is noteworthy that the definition of style, finish, and material for cabinets, crown, and valance, as well as the definition of hardware like hinges, drawer tracks, handles, puck lights, and strip lights, are performed with the aid of 3D models and catalog specifications from suppliers.

HTML is a very simple language that can be used to create both simple or complex web-based database applications. The simplicity of this language is its greatest strength. The power of HTML lies on the fact that it is a Markup language. This means that it is based on tags. For example, <p> marks the beginning of a paragraph and </p> marks its end. In order to author an HTML page, it just takes to know the tags and rules of how to combine the tags. Editing and saving a web page is as simple as writing a text and saving it with the extension ".htm" or ".html". Any text editor can be used. And testing the page requires only to go to the location where the file was saved and double-click the file to view it in a browser. There are quite a lot of teaching videos available for the learning process.

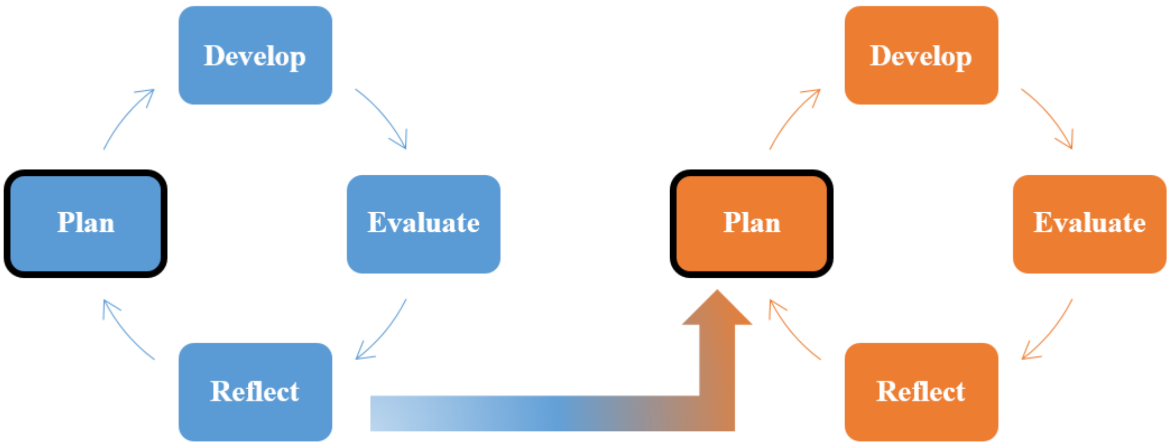
PHP is a language associated with HTML with the objective of collecting data from the forms and adding, delete, and modify data in a database. This language was used to control user access to the database. PHP is a scripting language. The script is executed on the server and the result is sent to the browser in the form of an HTML file. It is a text file that has extension ".php". A PHP script can be placed anywhere in an HTML file. In PHP, there is no command for declaring a variable. A variable is just a name that starts with the $ sign, and variables are automatically created at the moment a value is assigned to them. In PHP, variables can be declared anywhere in the script. However, a variable that is declared outside a function has a global scope and can be used only outside the function. In order to have access to a global variable from within a function, it is necessary to write the keyword “global” before the variable. A variable declared within a function has a local scope and can be accessed only within that function. Therefore, two distinct variables created in two different functions can have the same name, because they are local and recognized only within that function. This allows not only the reuse of functions but also simplifies the maintenance of the program in the future. This is especially relevant in relation to what was stated by Eastman et al, (2008), that BIM requires a large amount of data.

SQL stands for Structured Query Language and is a standard language for storing, manipulating and retrieving data in RDBMS databases. RDBMS stands for Relational Database Management System. The data in an RDBMS database is stored in objects called tables, and a table is a collection of data entries consisting of columns and rows, just like a spreadsheet. A table is a collection of smaller entities that can be addressed as an intercession between a row and a column. Each row is called Record and each column is called a Field. A Field is a collection of data related to specific information. A row is a collection of an instance from each field. A database is a collection of tables. Most of the actions that are needed to be performed in a database are done with SQL statements. SQL syntax is quite simple. For example, the statement, SELECT * FROM CUSTOMERS, retrieves every information contained in the table customers. There are different versions of the SQL language, but all versions support the major commands such as SELECT, UPDATE, DELETE, INSERT, and WHERE. SQL language is standard in all major databases such as MariaDB, MySQL, SQL Server, Oracle, Sybase, Informix, MS Access and others.

7. ACTION RESEARCH

The action research was applied in order to perform the instantiation of the proposed model and method. The two four-stage cycles of the action research shown in Figure 70, started with Planning the activities. The design and fabrication of a very simple kitchen were planned using BIM models interacting with a Web database application. The second step was the development of the planned activities. The third step is the observation and evaluation of the results in relation to the desired benefits planned in the first stage. And the fourth step was the reflection over the lessons learned. The reflections in the first cycle were used as an important source for planning in the first stage of the second cycle.

Figure 70 - A four-stage cycle of an Action-research

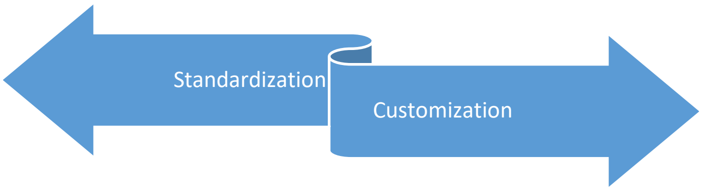


Source: The author.

As can be seen in Figure 71, Mass customization is the attempt to blend two opposing forces specified by Khalili-Araghi and Kolarevic (2016) as two contrasting concepts. On one hand, the manufacturers seek standardization in order to keep the efficiency of their systems, and on the other, designers seek the customization in order to meet the desires and needs of clients and users.

The action research was driven by three principles of MC stated by Hermann et al. (2014), which are, modularization, adaptability, and delaying of differentiation. Modularization allows variety through recombination of parts. Adaptability is a rapid adjustment of the production capacity, functionality, structure, and control to adapt to a custom product. Delaying differentiation is to postpone the point where a product takes its unique characteristic. The concept developed in the research and tried in the Instantiation, is that the use of BIM tools together with a web database application allows a trade-off between customization and standardization providing the benefits of both strategies.

Figure 71 - Opposing forces in Mass Customization



Source: The author.

7.1. First Cycle

The main participants in this phase of the research were the researcher, the firm's CEO, the design and production engineers, the CAD manager, the database administrator, and the CNC programmer. The researcher had previous experience in software development for the design and fabrication of kitchen and bathroom in an SME manufacturer. This knowledge allowed him to be more participative and interpretative. The researcher also had a good knowledge of the roles of each specialist in the company. This knowledge allowed him to play an active role in the research. The researcher along with a designer and an expert in digital fabrication played the roles of a Small Production Cell.

The approach adopted was a qualitative and verbal description of the phenomena observed. The analysis and interpretation of the collected data were performed through participant observation, interviews, and design's documents and contracts with clients.

7.1.1. First stage: Planning

The planning in the first stage in the second cycle begun with meetings with the CEO of the company. In the first meeting, the overall concepts of the proposed model and method in this research were discussed. The main objective of the meetings was to discuss the interconnection between the concepts of Custom-driven design, Mass Customization adoption strategy, BIM toward fabrication, and

Digital fabrication in Mass Customization as in Figure 54 and Figure 55. For example, the staff training plan that is part of the Mass Customization adoption strategy is related to the benefits that are sought with BIM toward fabrication. The creation of Small Production Cells related to the concept of Mass Customization adoption strategy is closely linked to the concepts of Custom-driven design and Digital fabrication in Mass Customization because a Small Production Cell must be an entity able to run both the design and the fabrication.

The activities that would take place in the first cycle were discussed in the second meeting with the CEO of the company. The main concern of the CEO was with regarding the oncoming benefits the company could have in supporting the research. The balance between cost and benefits shown in Figure 20, was discussed as part of the process flexibility required for a Mass Customization strategy. The researcher suggested actions toward the definition of the balance between the freedom that would be granted to the custom in individualizing their product versus the level of process standardization that is necessary to keep the manufacturing efficiency and efficacy. It was discussed also the fact that it is necessary to plan which parts of a cabinet would be digitally fabricated and which parts would be manufactured as a handcrafted piece.

Five activities were planned: (1) Apply the proposed method of BIM mediated MC to Engineered-to-Order cabinetry; (2) Develop and perform the MC Implementation Strategy; (3) perform experiments with Digital Fabrication in MC environment; (4) perform experiments with HTML, PHP, SQL and G_code in the context of the Web-Database Application; (5) Establish a process to create Revit Families.

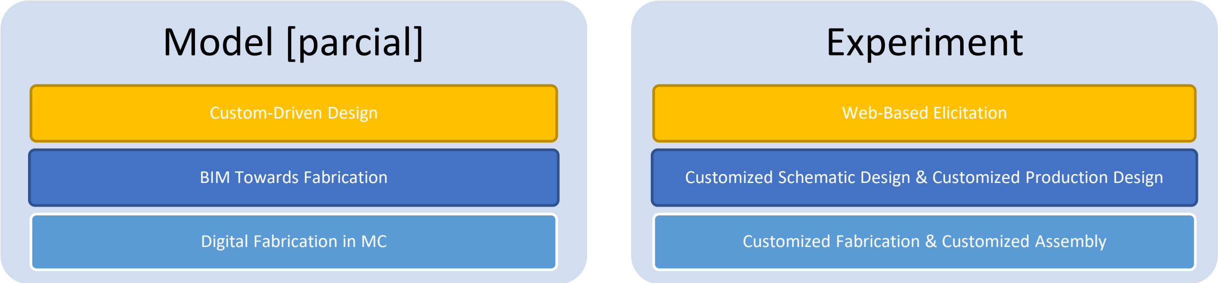
The strategy created for the MC implementation process consisted mainly in defining a set of attributes that would be customized, selecting a project to be designed and fabricated, and the creation of a prototype of a Small Production Cell among the research participants. The experiment with Digital Fabrication in MC consisted of the integration between geometry and data in order to match customer preferences and product specifications with the technical constraints related to Fabrication. The development of the web database application, encompassed studies with the selected tools in order to optimize the process of collecting information on customer preferences and product specifications, comparing this information with each other, and establishing design constraints due to construction requirements. The creation of Revit families of BIM modules for a simple five-cabinet kitchen was proposed to play with the changeable nature of a custom product in the creation of BIM model families and at the same time to get the research participants involved in the process.

7.1.2. Second stage: Development

BIM mediated MC applied to Engineered-to-Order Cabinetry

As shown in Figure 72, concepts from the model were explained with terminology that would facilitate the communication between the participants. The map shown in Figure 73 was adapted to the production flow of the company. For example, BIM Toward Fabrication in the proposed model, Figure 54, corresponds to the Customized Schematic Design and to the Customized Production Design concepts in the Experiment.

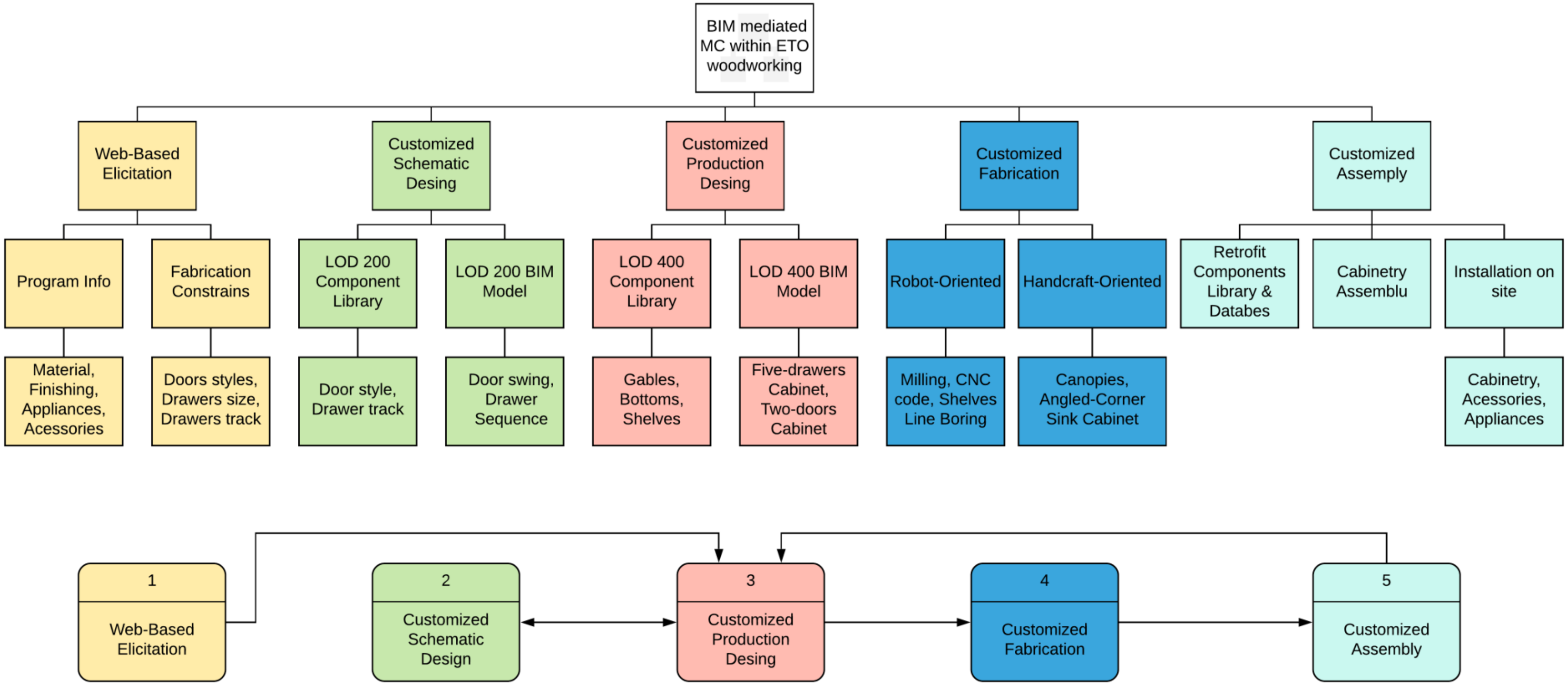
Figure 72 - Comparison between model and experiment concepts



Source: The author.

In regard to the **Web-based Elicitation,** it was discussed the process of collecting information on customer preferences and product specifications, comparing this information with each other, and establishing design constraints due to construction requirements. It was also planned for the transition between the current system based on Excel spreadsheets for the new Web Database Application system. The web-based system contains job specifications and fabrication constraints in MariaDB, the chosen Relational database. Some examples of job specification parameters are material, finishing styles, appliances, and accessories and some examples of fabrication constraint parameters are door styles and drawer tracks.

Figure 73 - BIM mediated Mass Customization within Engineered-to-Order woodworking



Source: The author.

The **Customized Schematic Design** corresponded to the preliminary conceptual design. A model of a simple kitchen was planned with elements represented graphically as generic objects with overall parameters like approximate height, width and depth of each cabinet their location and orientation and some non-geometric information like quantities and material which according to Reinhardt and Bedrick (2018) corresponds to BIM LOD 200. Revit templates and visual programming with Dynamo would replace AutoCAD preliminary drawings and generic design information stored in Excel spreadsheets.

The **Customized Production Design** corresponded to planning the detailed Fabrication and Assembly design. A model of the kitchen was planned with elements represented graphically as specific objects with complete information for fabrication and assembly and parameters like height, width, and depth with precision in millimeters. A model with rigorous and precise geometric and non-geometric information like quantities and material which according to Reinhardt and Bedrick (2018) corresponds to BIM LOD 400. Also, the Visual programming at Dynamo to allow accurate manufacturing information to be exported to the CNC machines, and lists of hardware and other materials being generated for the purchase order system. The researched company deals with inaccuracy in construction by creating interface elements between building components, whose accuracy is in centimeters, and the kitchen cabinetry, whose digital fabrication allows for precision in millimeters. These elements are finishing panels, fillers and fascias, which make the junction between the kitchen cabinetry and the walls, floors and windows.

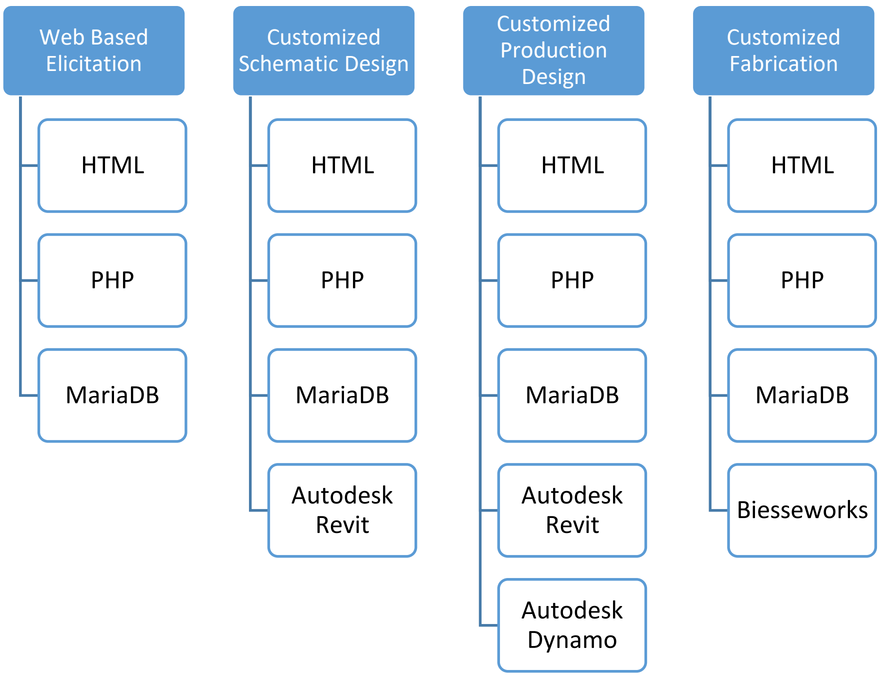
The kitchen cabinetry industry, as well as some other industries like the building elevator industry, require the definition of components intended to be the interface between millimeter-precision building elements and centimeter-precision building elements.

The **Customized Fabrication** corresponded to a search for a flexible production system, the definition of the attributes to be customized, and the definition of which parts would be digitally fabricated and which ones would be handcrafted. These decisions should rest on technical constraints and the relation cost/benefit. Biesseworks is a native software of the CNC machine used in the experiment. Biesseworks generates G-Code. Information transferring from Revit to Biesseworks through Dynamo can be done through SAT and STL geometric files, or by CSV or Tab-delimited text files. Tab-delimited text files were the chosen option.

The **Customized Assembly** corresponded to the logistics prescribed by Zipkin (2001) for delivering a customized product. The company uses at this stage of the production flow, the services of a company specialized in delivery. This, according to Zipkin, is the most adopted solution by Small and Medium Engineered-To-Order companies. It was planned the creation of “as-built” models for post-installation services and a system to create new patterns for BIM library, according to each category defined by Woodbury (2010) and shown in Table 4. It was also planned for this phase the creation of an automatic system to update the costs of each component of the BIM library, in order to get more accuracy in future job quotations. For this purpose, it should be used the web database application developed with HTML / PHP and under the MariaDB relational database.

Figure 74 shows the relation between the Instantiation tools and the experiment concepts. Because there is design and fabrication semantics built into the web database application, the Web-Based Elicitation tools are also relevant to the concepts of Customized Schematic Design, Customized Production Design and Customized Fabrication.

Figure 74 - Instantiation tools x experiment concepts



Source: The author.

Figure 75 shows through colors, the association between the method steps and the model concepts terminology created in the experiment. It shows also that there is a library of pre-built components[25] for items that can be parameterized. For the design and fabrication of fully customized elements, there is a library of parts[26] that can be combined to create a unique component. The joint use of the library of pre-built components with the library of parts is helpful to attend the cautiousness prescribed by Zipkin, according to which, only the attributes of a product that differ sharply from one client to another should be customized. This is a driving-factor for having the process flexibility appointed in Figure 53.

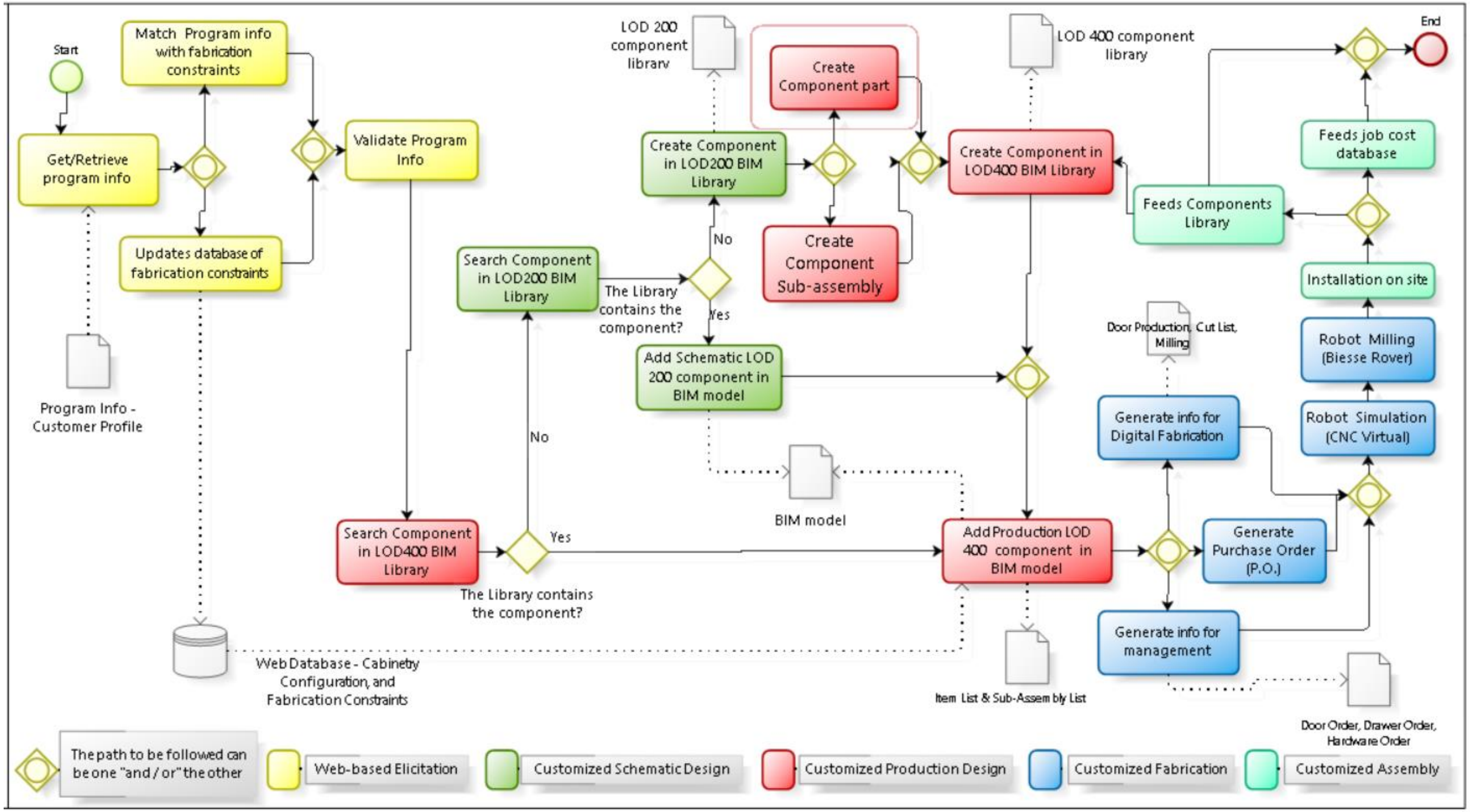
The libraries of components were planned following suggestions by Kieran and Timberlake (2004) to use Object-Oriented Programming (OOP), concepts largely used by computer specialists. OOP allows the development of more user-friendly interoperability between design and fabrication software. Simpler interoperability is important at least in the early stages of the implementation of Mass Customization because the manufacturing of some components is outsourced and communication with these sub-contracted companies should be as simple as possible.

MC Adoption Strategy: Implementation process and new roles

The strategy created for the MC implementation process was adapted from the BIM adoption strategy for subcontractors and fabricators suggested by Eastman et al. (2008) illustrated in Figure 2. Both BIM and MC have an impact not only on processes but also in people. And in both cases, implementation is not simply about automating existing operations, but it is to enable new workflows and processes. Both in BIM and MC, the implementation strategy must go beyond planning new software and hardware acquisitions and defining the staff training. It must be a thorough plan to get the staff involved and committed from the very beginning. But, due to the fact that concepts related to the BIM-mediated Mass Customization method are interdependent, as shows Figure 76, there is an overlap among the implementation activities in the context of Mass Customization.

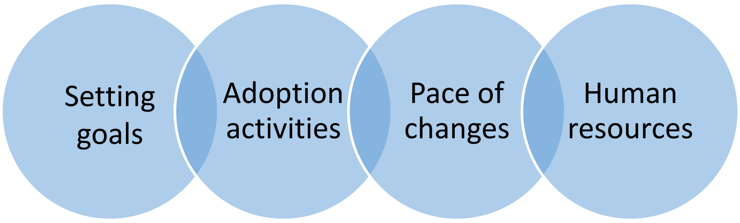
[25] One-door boxes, two-door boxes, one-drawer boxes, two-drawer boxes, three-drawer boxes
[26] Standard-Left-gable, L-Left-gable, J-Left-Gable, U-Left-gable, Standard-right-gable, L-Right-gable, J-Right-Gable, U-Right-gable, Standard-top, L-Top, J-Top, U-Top, Standard-bottom, L-bottom, J-bottom, U-bottom, and so on…

Figure 75 – Concepts of the experiment embedded in the method



Source: The author.

Figure 76 - Implementation Strategy of BIM mediated Mass Customization method

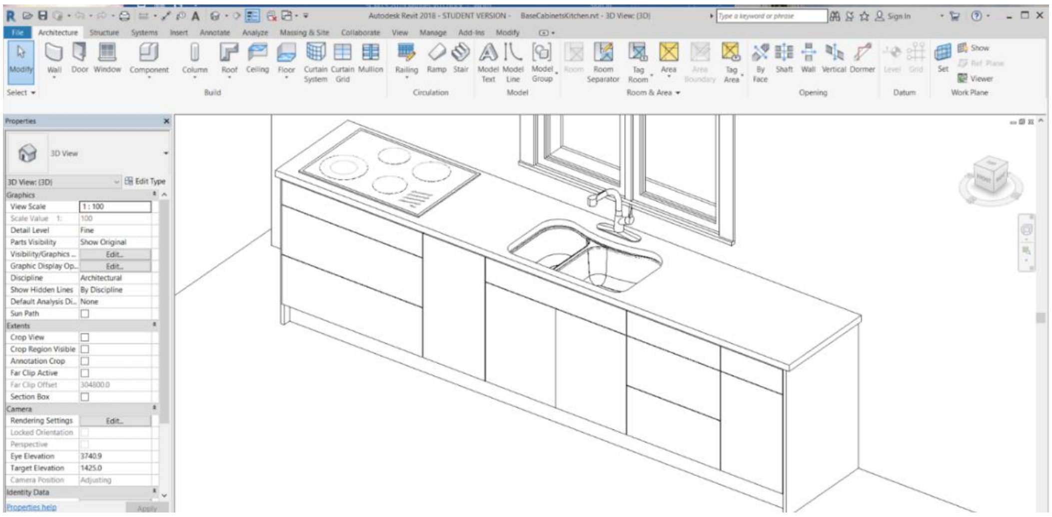


Source: Adapted from Eastman et. al. (2008).

The first stage is related to the MC Adoption Strategy shown in Figure 54. This step defined a set of attributes that would be customized. The appropriate level of details was set, both, for preliminary design and the details for the fabrication design. This stage encompassed the definition of how, when and by whom the library of components would be created, and the information flow.

In the second stage, it was chosen a very simple design of a kitchen with only five cabinets as shown in Figure 77. It was planned which would be the BIM models to be created. The simplicity of the chosen project was considered for training the staff with new tools and new processes, and to get the necessary commitment of each professional. Through periodic meetings, the professionals were made aware of the need to work collaboratively as a team.

Figure 77 - Kitchen designed and fabricated in the first cycle

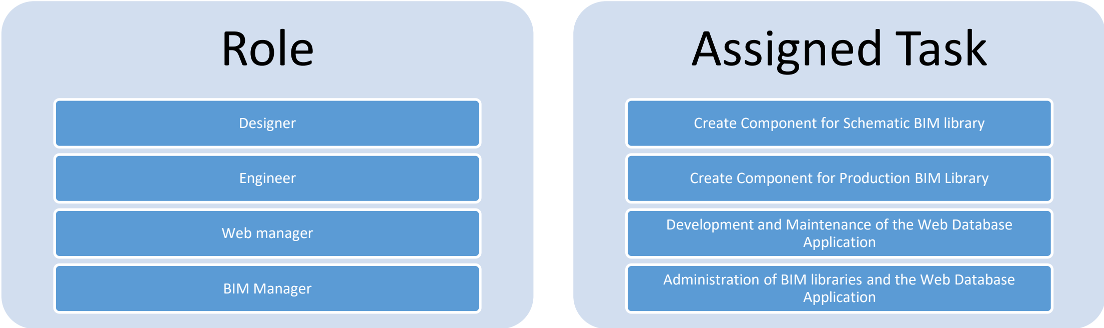


Source: The author.

The third stage was the definition of the pace of changes, which took in account not only the need for staff training but also the time required for the adaptation of clients, third party professionals, and suppliers with new processes. Having been made aware that BIM is disrupting technology, the company's CEO requested the least possible disruption not only in the manufacturing process but in the interactions with customers, suppliers and, third party professionals. It was not necessary to plan a phased replacement of the existing CAD workstations to BIM workstations because the company has only a few computers.

The fourth stage corresponded to the creation of a prototype of a Small Production Cell, as Figure 57 expresses, which is a production unity under the MC Adoption Strategy. As for this stage, it was considered that successful adoption of BIM requires that the people assigned to the new roles have the appropriate skills and are fully committed. The relation between roles and skills is presented in Figure 65 and the relation between roles and tasks are summarized in Figure 78. Two keys roles are the Web Manager and the BIM Manager. Both must be able to create components for the libraries, both schematic and production. They are responsible for the technical support regarding the exchange of information and collaboration among the Small Production Cells. The Web Manager administers the database, granting and revoking access permissions, and watching over the security issues regarding the database. The BIM Manager develops the interoperability between design and CNC machine computers by developing visual programming in Dynamo and creating Tab-Delimited text files. This stage considered the long-term effects of the new roles not only on business but also on staff and tried to develop a policy for training and to appoint the right professional for the right role. It was also considered the necessity of a new remuneration policy with the objective of ensuring the stability of the team in the long term and stimulate each professional to move out of their comfort zone toward new technology. The four stages are deeply intertwined, as Figure 76 suggests and as they are in line with the Management Toward Collaboration and the Responsible Freedom concepts discussed in the Constructs proposition chapter.

Figure 78 - Assigned tasks for each role



Source: The author.

Web database applications can enhance the application of BIM models in manufacturing, by allowing the design to be done in one location and manufacturing elsewhere, but a successful MC implementation must be a thorough plan that gets the staff involved and committed from the very beginning. Those conclusions are in pair with Longhui (2018), who identified 47 obstacles to the implementation of BIM, most of which are human-related and not related to technology. As well as with Tyl, Lizarralde, and Allais, (2015) who concluded that economic activities that use resources available locally and generate products for the local community have a great impact not only in the economy but also in the ecology and society.

Digital Fabrication in MC: Simplified experiments

The experiment with Digital Fabrication in MC consisted of the integration between geometry and data in order to match customer preferences and product specifications with the technical constraints related to Fabrication. This integration, according to Khalili-Araghi and Kolarevic (2016) is part of the process to achieve two desirable but incompatible features: the ability to meet the demands from customization and the desire of the manufacturers for standardization for the efficiency of the production.

The first activity was the design and fabrication of a scaled set of cabinets with the objective of experimenting with the balance between the parametrical variation needed in customization with the constraints required by fabrication and code compliance described in Figure 53. A typical modular kitchen has mainly two groups of cabinets. One that sits on the floor and another that is hanging from the wall. A cabinet from the group that sits on the floor was modeled and manufactured. The main parts in this type of cabinet that are common to all of them are the left-gable, right-gable, bottom, and back. The dimensions of those parts are simply parametrical variation needed in customization. But there is one part with constraints required by fabrication. If the cabinet is less than 200 mm wide or less than 350 mm deep, it must have a full panel on top, otherwise, it has two rails as shown in Figure 79. The two cabinets in the figure were modeled with the same family created with constrained parameters. The constraint would define whether the cabinet should have a single Top or two Rails.

Geometric parameters from the model and information and data for CNC machining were transferred from Revit to a CNC through a Drawing Exchange Format (DXF) file. Geometry in the DXF file must follow a specific structure for naming the layers, that is based on the tooling on the CNC machine. The layer name contains also predefined rules for machining operation.

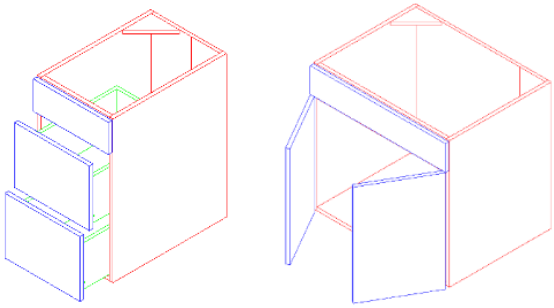
Figure 79 - Scaled cabinet fabricated in laser CNC machine

Source: The author.

After the design and fabrication of the scaled models, the participants of the Small Production Cell fabricated the kitchen that had been chosen in the MC Implementation strategy. The BIM models related to the planned kitchen is shown in Figure 77, and it comprises five modules whose sketches are shown in Figure 80 and Figure 81. A box with two drawers was used under the stove and a box with two doors was used under the sink. Besides those two, there were three more cabinets: a box with three drawers, a box with left-swing-door and a box with a door swinging right and a drawer on top.

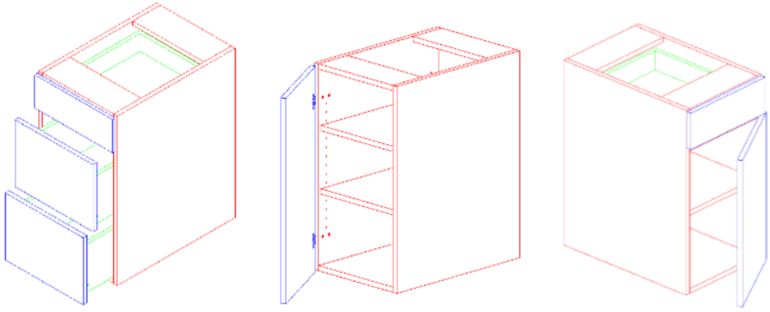
Regarding the concept of Digital Fabrication in MC, shown in Figure 54, the Small Production Cell shown in Figure 57, performed the fabrication and installation of the experiment’s kitchen. This action corresponded to a concept from Iwamoto (2009) who considers Digital Fabrication as part of a broader concept of CAD/CAM and defines it as the use of digital data to control a fabrication process. Dynamo's visual programming was used to export Revit parameters, shown in Figure 82, to the CNC BiesseWorks software through Excel spreadsheets as shown in Figure 83. The list of cut parts and the specification of hardware to generate purchase orders were among some of the accurate design information necessary for the manufacturing process that was exported from Revit to the Excel spreadsheets. The experiment used Dynamo for reading from Revit and saving into Excel spreadsheets but the web-based database application was scheduled to replace the information stored in excel worksheets in the second cycle. Currently, the company uses AutoCAD to perform design and Excel spreadsheets to store both, the preliminary design information and manufacturing details.

Figure 80 - Two-drawers and two-doors sketches



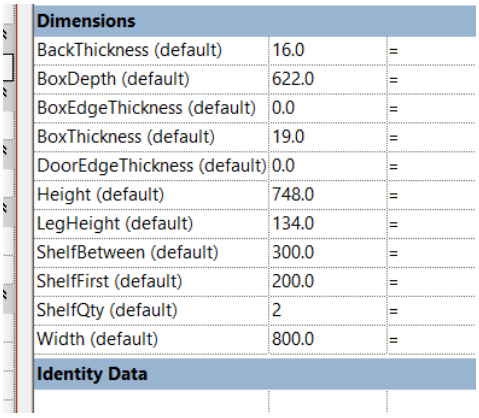
Source: The author.

Figure 81 - Three-drawers, left-swing-door, right-swing-top-drawer sketches



Source: The author.

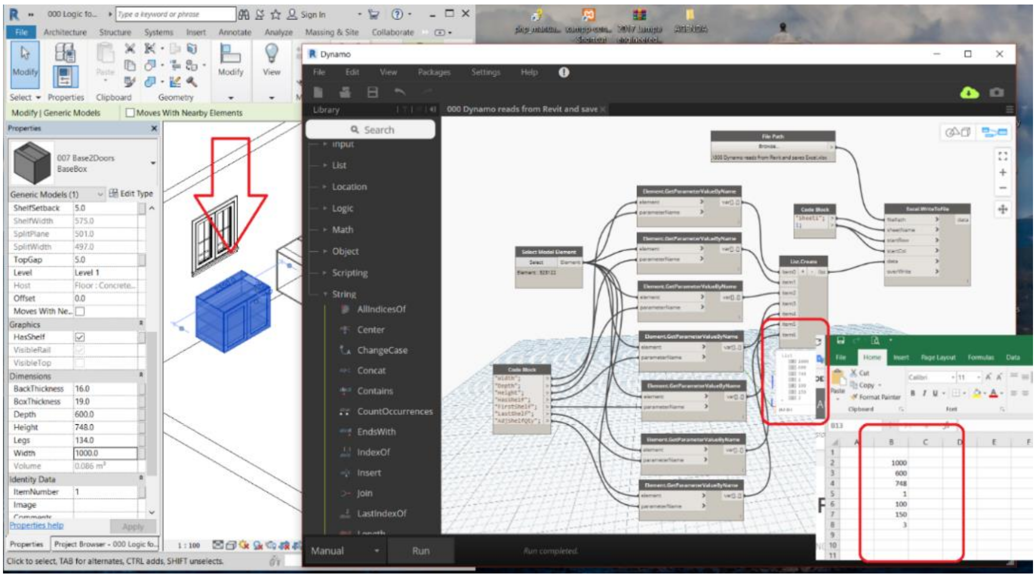
Figure 82 - Fabrication parameters on Revit Models



Dimensions		
BackThickness (default)	16.0	=
BoxDepth (default)	622.0	=
BoxEdgeThickness (default)	0.0	=
BoxThickness (default)	19.0	=
DoorEdgeThickness (default)	0.0	=
Height (default)	748.0	=
LegHeight (default)	134.0	=
ShelfBetween (default)	300.0	=
ShelfFirst (default)	200.0	=
ShelfQty (default)	2	=
Width (default)	800.0	=
Identity Data		

Source: The author.

Figure 83 - Exporting parameters from Revit to Excel through Dynamo



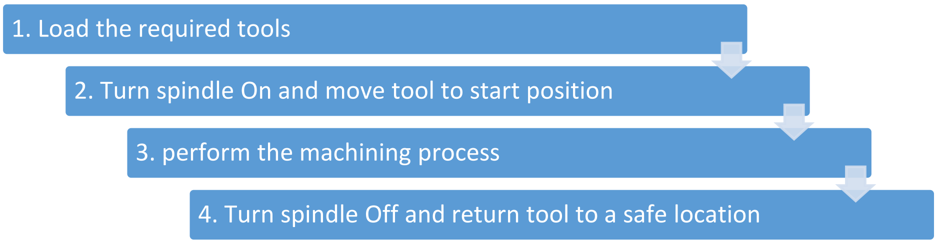
Source: The author.

Custom-Driven Design: Web Database Application

In order to develop the web database application, some studies were taken with the chosen tools: HTML and PHP to create the web-site and MariaDB as the Relational database. This was in line with the opinion of Farr, Piroozfar, and Robinson (2014), which stated that researches in user-friendly web database applications are still needed in the AEC industry. The customization of a kitchen would begin with designers completing a web-based database containing project specifications and design constraints.

As for the interoperability between BIM models and CNC machine, some experiments were taken in BiesseWorks and G-Code using a BIESSE ROVER SKILL 15.36 G FT ARTECH machine to fabricate G-Code created models, covering all the basic codes that are common to every CNC machine like rapid-moving, drilling, contouring, roughing, pocketing and cutter compensation. Cutter compensation is an offset toward the left or the right on the cutting path according to the tool dimensions. Special attention was given for the clockwise and counterclockwise circular interpolation. Before running the programs in the real machine, they were run in the Biesseworks simulator. Submitting the programs through simulator detected errors and prevented damage to the machine. G-Codes are grounded into Modal functions and Nonmodal functions. A modal function is something that stays on in the CNC controller until the machine is turned off. Nonmodal functions are tasks executed in a finite time Because G-Code is a low-level language, looping processes required a combination of Modal codes (which perform actions indefinitely), with Nonmodal codes (tasks that are executed in a finite time). The G-code programs followed the steps shown in Figure 84.

Figure 84 - Sequence of tasks in G-Code programming



Source: The author.

BiesseWorks is the programming language developed by the maker of the CNC machines at the company. Experiments were carried out with Dynamo by exporting SAT and STL geometric file types, and by CSV and Tab-delimited text-type files. Tab-delimited text files were the chosen option due to recommendation of Luth (2011) of a simplified interoperability, but also due to the limits on digital fabrication identified by Shelden (2014), and according to Eastman et al. (2008) that stated that the ability to provide an effective communication with stakeholders outside the fabricators organization, such as suppliers and component installers is a requirement for BIM systems applied to Engineered-to-order components fabricators.

The following paragraphs contain some highlights of the features from the main tools that were used to develop the web database application, i.e.

HTML, PHP, and MariaDB.–The researcher learned HTML and PHP through W3Schools[27], a web site optimized for learning, testing, and training. The program developed in the research started very simple but structured to grow in complexity into a well-elaborated web application.

HTML provided the structure for the page, and CSS and Javascript were used as associated languages. CSS was used to control the appearance of the page and Javascript was used to control the behavior of the page showing, hiding, formatting or adding new elements or content on the page. The power of HTML lies on the fact that it is a Markup language. This means that it is based on tags. For example, <p> marks the beginning of a paragraph and </p> marks its end. In order to author an HTML page, it was only necessary to know the tags and rules of how to combine the tags. Editing and saving a web page was as simple as writing a text and saving it with the extension ".htm" or ".html". Any text editor could be used but Notepad was the adopted option. And testing the page required only to go to the location where the file was saved and double-click the file to view it in a browser. There were quite a lot of teaching videos available for the learning process. Figure 85, Figure 86, and Figure 87 are excerpts from the developed web-database application and show respectively a simple web page, its HTML scripting code, and the CSS file used to control the appearance of the page.

PHP was used associated with HTML to control access to the database. As it is with every programming language, it is highly recommended to use comments in order to create an easy to understand code. This recommendation was followed in the experiment. Codes created in this researched were full of comments because as the workflow in a Mass Customization environment changes frequently, so it is with its applications in the computer. Adding comments was an important policy adopted because they remind what the programmer was thinking when writing the code. A process that required special attention during PHP programming was the creation of variables. Although PHP codes are not case-sensitive, variable names are case-sensitive. This means that &color, $COLOR, and $Color are three different variables. The

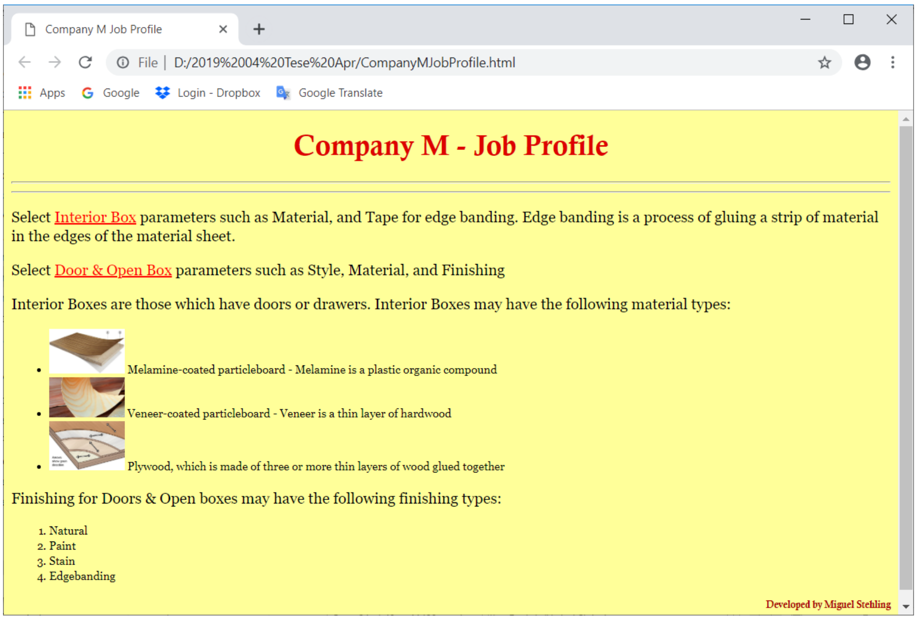
[27] https://www.w3schools.com/html/

same guidelines adopted in the creation of parameters for the Revit libraries were followed for creating variables in PHP. The pattern is: Names should be as meaningful as possible, and they should be created uppercase for the first letter on each word and lowercase for the remaining ones, without spaces between words. Example: BackThickness, BoxWidth, BoxHeight, and BoxDepth. The only difference in relation to Revit is that PHP variables start with the $ sign and the Revit parameter does not. Another pattern established was concerned with the scope of the variables. Scope of a variable refers to the part of the script where the variable can be referenced or used. It was defined in the experiment, that whenever possible a variable should have a Local scope and only rarely, a variable should have a Global scope. This principle was adopted because the use of global variables makes it difficult to reuse functions. The reuse of functions is essential in Mass Customization.

SQL can be learned through the W3Schools[28] a web site but as the researcher already had experience with database administration, he did not take the course. SQL was used to execute queries, retrieve data, update, add and delete records from the database. SQL was used also to set permissions for users reading and writing on tables. This is a crucial feature in the context of a Custom-Driven Design, Figure 55 because project documents generated through the web must be reliable and its access history must be traceable. SQL commands were embedded in PHP scripting files, to access data from a database. MariaDB was the chosen RDBMS database. MySQL was the RDBMS initially intended to be chosen, but MySQL is not a free open-source anymore, and its founders have developed MariaDB to remain a free open-source and fully compatible with MySQL. Therefore, this research used MariaDB instead of MySQL, and Figure 88 shows a screen from **phpMyAdmin,** a free tool chosen to handle the administration of MariaDB over the Web. Written in PHP, phpMyAdmin is one of the most popular, free and open-source administration tools for web hosting services.

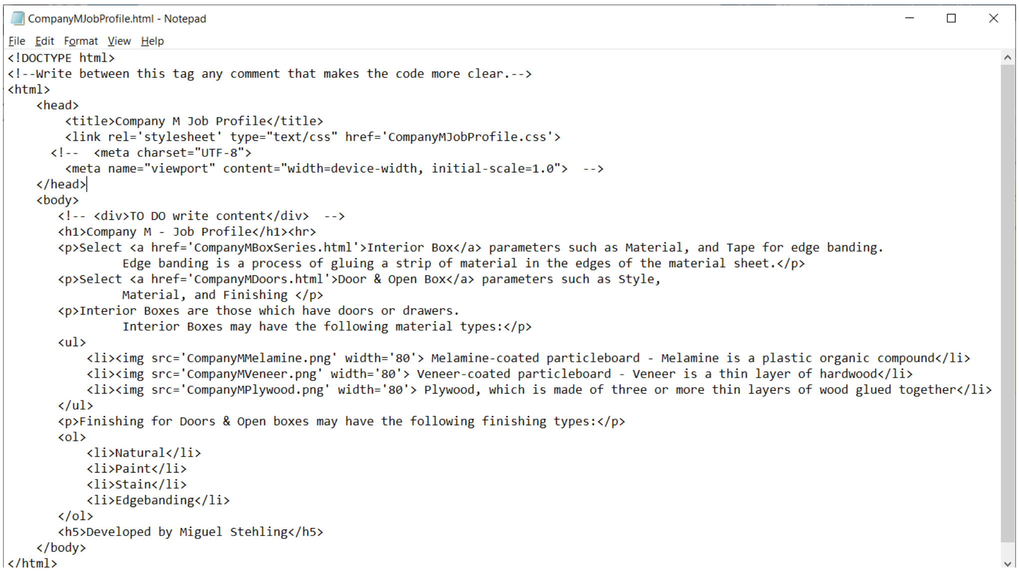
[28] https://www.w3schools.com/sql/

Figure 85 – Web page for the Job Profile



Source: The author.

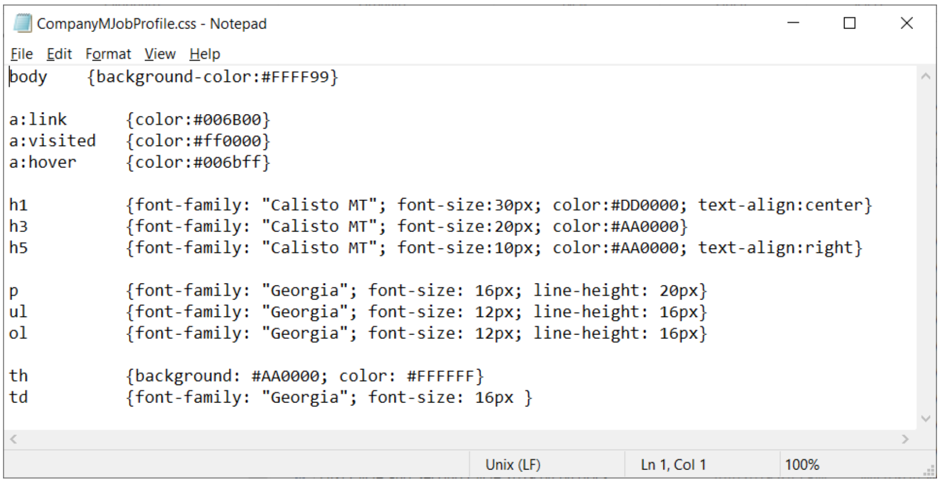
Figure 86 -HTML script code for the Job Profile




```
<!DOCTYPE html>
<!--Write between this tag any comment that makes the code more clear.-->
<html>
    <head>
        <title>Company M Job Profile</title>
        <link rel='stylesheet' type="text/css" href='CompanyMJobProfile.css'>
      <!--  <meta charset="UTF-8">
        <meta name="viewport" content="width=device-width, initial-scale=1.0">  -->
    </head>
    <body>
       <!-- <div>TO DO write content</div>  -->
       <h1>Company M - Job Profile</h1><hr>
       <p>Select <a href='CompanyMBoxSeries.html'>Interior Box</a> parameters such as Material, and Tape for edge banding.
                Edge banding is a process of gluing a strip of material in the edges of the material sheet.</p>
       <p>Select <a href='CompanyMDoors.html'>Door & Open Box</a> parameters such as Style,
                Material, and Finishing </p>
       <p>Interior Boxes are those which have doors or drawers.
                Interior Boxes may have the following material types:</p>
       <ul>
           <li><img src='CompanyMMelamine.png' width='80'> Melamine-coated particleboard - Melamine is a plastic organic compound</li>
           <li><img src='CompanyMVeneer.png' width='80'> Veneer-coated particleboard - Veneer is a thin layer of hardwood</li>
           <li><img src='CompanyMPlywood.png' width='80'> Plywood, which is made of three or more thin layers of wood glued together</li>
       </ul>
       <p>Finishing for Doors & Open boxes may have the following finishing types:</p>
       <ol>
           <li>Natural</li>
           <li>Paint</li>
           <li>Stain</li>
           <li>Edgebanding</li>
       </ol>
       <h5>Developed by Miguel Stehling</h5>
    </body>
</html>
```

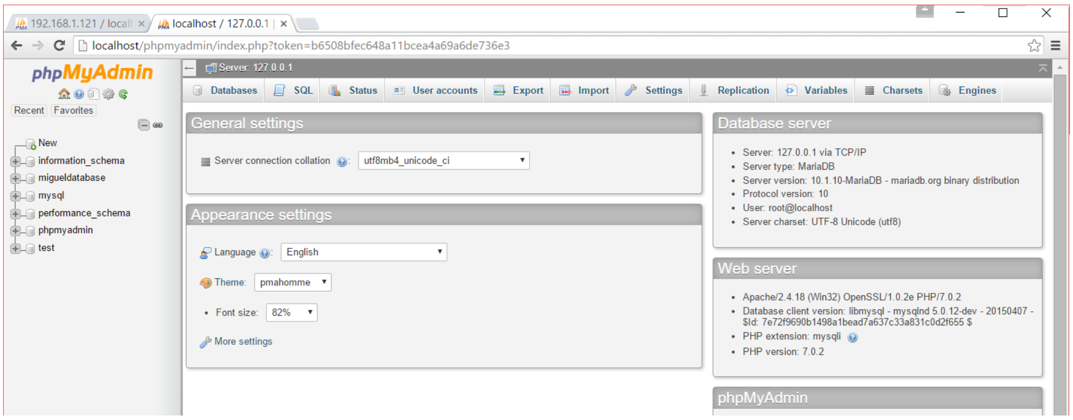
Source: The author.

Figure 87 - CSS script code for the Web page



Source: The author.

Figure 88 - phpMyAdmin, a database administration tool



Source: The author.

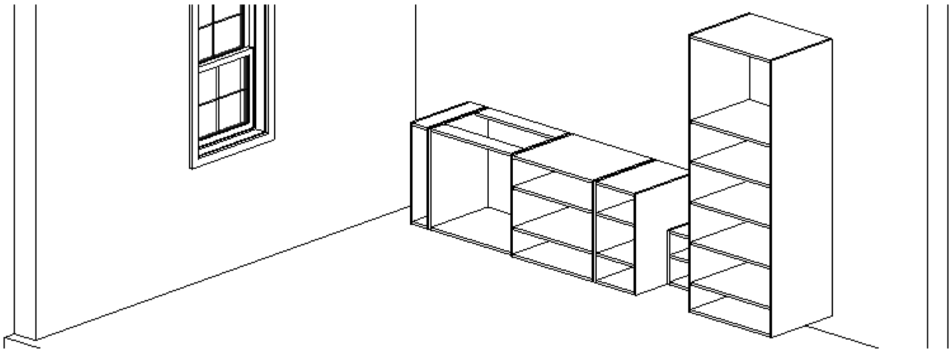
BIM Toward Fabrication: Process to create a Revit Family

Due to the changeable nature of a custom product, the proposed method aimed at making it easier, the update and maintenance of the building component Library. In order to make it feasible, it was applied the principle of hierarchy in the creation of BIM model families. Hierarchy means that each component family can inherit geometry, parameters, and constraints from its parent family. At the top of the hierarchy of a building module, there is a group called Category shown in Figure 89. Categories are the macro elements of a building such as walls, doors, floors, furniture, and appliances. The cabinetry library was built under a Category called Component. Categories have groups of Families associated with them. A family is a group of elements with a common set of Parameters (properties), identical use, and similar geometry. But Family is still a very broad level in the hierarchy. Each variation of a Family is referred to as a Type. The actual objects in a building model are called Instances. An Instance belongs to a Type, Type, in turn, belongs to a Family, and Family is part of a Category. In the kitchen cabinetry library, there were, among others, one family called Base-One-Door. Under this family, there were the Base-One-Door-Left-Swing and the Base-One-Door-Right-Swing Types. Figure 90 shows six instances of cabinets created from the same family, but different types.

Figure 89 - Hierarchy among models of a building

Source: The author.

Figure 90 - Six cabinets from same family



Source: The author.

Product Families were created using the algorithm concepts of Object, Class, and Method from Object-Oriented Programming. This policy allows the library of components to be best suitable for future maintenance. Besides that, the creation of families was guided by a careful definition of parameters and constraints following predefined patterns. These actions were in line with the opinion of Schneider (2014) who stated that a Product Family is a combination of a generic structure with a set of variables and constraints designed to allow flexibility in the creation of a product. And that a Product Family must be consistent with the customer requirements while ensuring that no constraint is violated.

When creating a family, the template was chosen carefully, because the created family inherits the properties of the template and once the template is chosen, it is impossible to change it. The template is a building block to the family. It contains information that is used to place the family in projects. If the chosen template is not ideal, it is necessary to create the family again. Most of the family templates are host-based, like Wall-based, Ceiling-based and Floor-based. For example, if a family is created using a Floor-based template, that family can only be inserted into floors and it cuts an opening in the floor. For the objects created in this research, the best choice was Line-based templates. Line-based templates use two pick points to place the family in projects. Line-based creates families that can be displayed in any view and are unhosted families.

One important decision made in the experiments was concerning the origin point of the families. Two options were tested. The creation of families with the insertion point in the center of the component, and with the insertion point in one of the sides. Determining the appropriate insertion point is necessary to help to place the family in a project. As the experiment progressed, the best choice appeared to be the insertion point in one of the sides of the cabinet.

In order to create more sturdy BIM library components, and to simplify the process of the library's updating and maintenance in the future, and to make it easier the communication among professionals during design and fabrication, some guidelines were defined for creating Revit Families:

1. The first guideline was the definition of a pattern for parameter names. Names must be as meaningful as possible, and they must be created uppercase for the first letter on each word and lowercase for the remaining ones, without spaces between words. Example: BackThickness, BoxWidth, BoxHeight, and BoxDepth.

2. Wherever possible, dimensions should be placed on reference planes and not geometry.

3. Preferably, dimensions should be placed from the stronger plane first, to the weaker second. for example, an independent plane is stronger than a dependent one.

4. Whenever is necessary to lock a geometry, preferably it should be locked to a reference plane and not to another geometry.

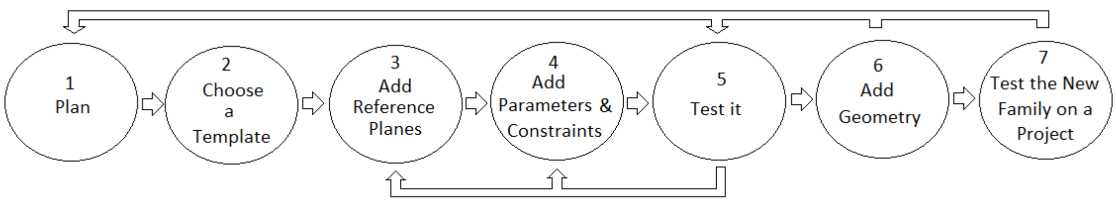
5. Testing should be done frequently to ensure that everything is performing as expected. This should not be considered a waste of time, because if time is

saved from testing, more time is wasted at the end, trying to figure out what went wrong.

6. Arrays can be a very useful resource, but they often have awkward behaviors. When using arrays, one must start with a very simple routine, and gradually increase the degree of complexity of the function. And it is necessary to test at each step.

The flow of activities adopted as the process to create a BIM family is shown in Figure 91 Figure 91and it comprises seven recursive steps. The **first** step is to plan carefully what to do based on what behavior is required from the family. This is done through notes and sketches. The **second** step is to select a good template file. Every BIM tool offers several template files. Each one has predefined built-in behaviors. Those behaviors are imparted to the created family. So, the right template must be chosen in order to get the desired behavior. The first and second steps should be joint work between the members of the Small Production Cell. The members of the Small Production Cell are the Custom-Driven parametric design specialist, the BIM toward fabrication specialist, and the specialist in fabrication and installation.

Figure 91 - Process to create a Revit Family

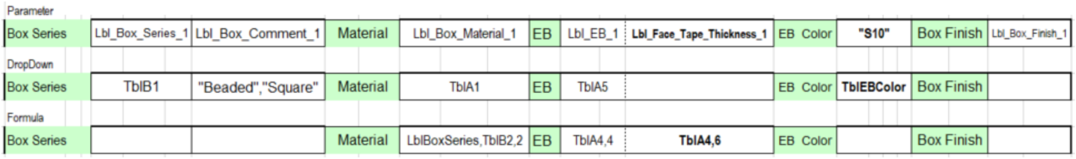


Source: Adapted from Aubin (2011).

From the third step to the seventh, the tasks may become recurrent. The **third** step is to add reference planes. Reference planes are the best resources to set up the form and structure of the family and to define its geometric limits and characteristics. It's a critical step. This step should be designed carefully so that the geometry can behave the way it is expected to behave. The **fourth** step is to add parameters and constraints. Parameters and constraints add intelligence to the family somewhat differently from one another. A parameter is a rule with which the user interacts with. Parameters are the changes that the user is allowed to perform when the family is inserted in the project environment. A constraint is a lock in the design, a characteristic in the environment that the user cannot change. It's a permanent behavior of the family, that users cannot modify. Preferably, parameters and constraints must be added into reference planes and not into geometry. Parameters and constraints work better when linked into reference planes, not geometry. The **fifth** step is to test to make sure all is behaving in an expected way. If not, return to step four or step three. The **sixth** step is to add geometry. The geometry must be attached to reference planes, which at this point should be driven by the parameters and constraints. The **seventh** step is to test the new family on a project. After making sure that the geometry, reference planes, parameters, and constraints are working exactly the way it was expected, there is another test and it is when the newly created family is loaded into a project and tested whether it is working according to the planned in the first step.

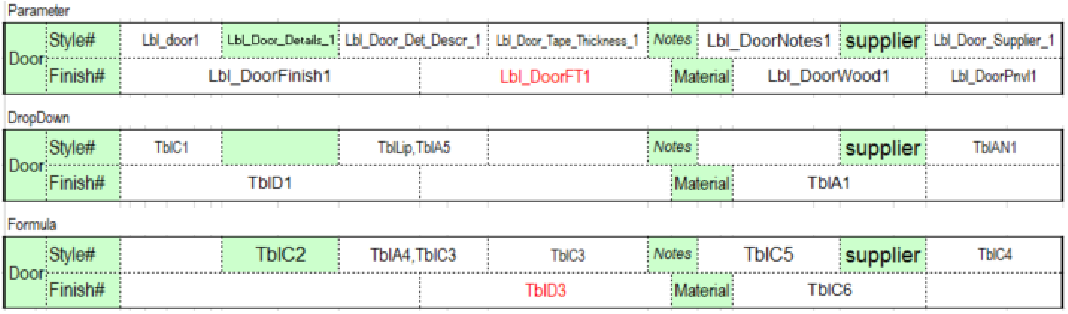
The System for Detailing a Customized Design for Digital Manufacturing was initially developed using Microsoft Visual Basic for Application in Excel Spreadsheets. The reason is due to three factors: The **first** reason is related to the fact that VBA is a very easy tool to be used by many professionals in the woodworking industry. The **second** reason is that a system developed in VBA offers almost immediate conditions of use. This was an important decision-factor due to the short time available for the research and due to the fact that the company CEO was not willing to wait for a more complex system to be developed. The **third** reason is the outcome of the second one. It was decided that the web_based database system planned at the beginning of the research would be developed in parallel to the Excel system because a database system has a longer development cycle and also because a web_based system requires an additional information security subsystem. The system developed in VBA contained global variables for the specifications of Boxes, doors, drawers, gables, crown valance, countertop, glass doors, glass shelves, and pulls. Some of these variables are shown in Figure 92 and Figure 93. These global variables were transferred as parameters to each cabinet inserted in a project.

Figure 92 - Parameters for boxes



Source: The author.

Figure 93 - parameters for doors



Source: The author.

7.1.3. Third stage: Evaluation

. According to Bock (2015), the application of the concept of robot-oriented design in a mass customization strategy should increase gradually because automation in the AEC industry is still at the innovation stage and is developing very slowly due to the complexity of the products and to the few resources that are applied in research and development. Therefore, the first cycle comprised of preliminary testing of the method and tools.

For this reason, it was decided to perform the design and manufacturing of a small and simple kitchen. It consisted of testing a limited scope of parameters from the kitchen components. It was designed a small kitchen with just a few cabinets leaning on the floor. In addition to that, it was considered cabinets without much complexity, just a few parameters to control drilling on the gables to host shelves, drawers, and doors. The first cycle was also dedicated to getting the commitement of design and fabrication specialists to the new technology

7.1.4. Fourth stage: Reflection

The fourth stage in the first cycle was a reflection to express the lessons learned in the first cycle. Corrections were made to feed the planning stage in the second cycle.

On Digital Fabrication in MC and Custom-Driven Design, the first cycle focused more on parameterization and the second cycle should focus on creating and fabricating more complex models. It should be explored the resource of nesting families and the definition of a process for creating BIM model libraries for Engineered-to-Order building components.

7.2. Second Cycle

The second cycle began with the expression of the lessons learned in the first cycle. Then a new action plan was designed based on the techniques and tools tested in the first cycle. It included the creation of product families, the process for creating libraries for kitchen cabinetry, and the hierarchy of components in a job. In addition to that, the requirements and desired characteristics of the artifacts were reviewed, as well as their limits and relationships pointed out by Zipkin (2001). In the second cycle, the researcher, working with the team selected to act as a Small Production Cell, developed the BIM models and the text-based communication between computers from design and the CNC machines.

The Small Production Cell within the MC Adoption Strategy has four main roles: (1) The creation of BIM library for the basic design; (2) the creation of the BIM library for the fabrication design; (3) the management of the web database application, by performing maintenance in the application and granting and revoking access permissions to database; (4) The generation of CNC machine programs for the parts that are digitally fabricated and the management of the handcrafted parts. One role can be performed by more than one specialist, and one specialist can perform mode than one role depending on the size of the company or the size of the Small Production Cell. In the experiments in the second cycle, one specialist performed two roles, the creation of BIM library for the basic design, and the creation of the BIM library for the fabrication design.

MC requires standardization, not of products but of processes, and one member in the Small Production Cell must be responsible for this task. The standardization of processes is as complex as higher is the level of customization that is offered. For example, the standardization of MC processes for a company that customizes cabinets with regular flat panels is much less complex than that of a company that offers several types of panels, like L-shape, J-shape, and U-shape shown in Figure 96. These components serve as an interface between building components fabricated with millimeter-precision and building components fabricated with centimeter-precision.

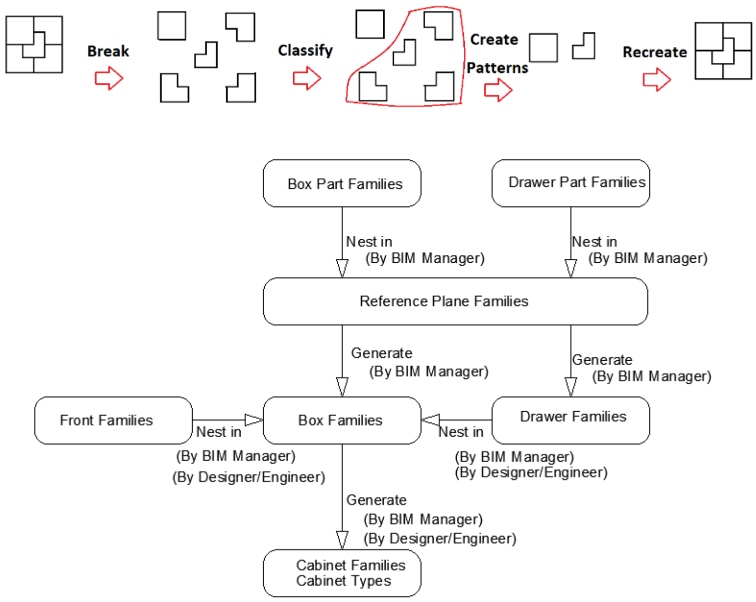
7.2.1. First stage: Planning

The planning in the first stage in the second cycle begun with setting goals according to the results from the first cycle and making efforts to get the staff committed in the implementation process. The goals for this cycle were: (1) The development of a process for **creating libraries of BIM models** by nesting parts of components generated with patterns; (2) The definition of **hierarchy of components in a job**; (3) The definition of hierarchy for **parameters inheritance** among Revit families; (4) Experiments with two **Digital fabrication techniques:** Folding and Contouring; and, (5) **Exporting parameters** from Revit through text files generated in Dynamo's visual programming environment.

The process developed for creating libraries of BIM models for woodworking cabinetry is a four-step process based on the technique of nested families and shown in Figure 94. The first step was to break a complex component into simple subcomponents or parts. The second step was to classify the parts by degree of geometric a parametric similarity. The third step was to group parts with similar parameters creating patterns. The fourth was to create the original complex component using the patterns. The creation of parts of cabinets and nesting them in patterns is in line with Woodbury (2010) that suggests breaking a complex body into simple components. The objective of the hierarchy of components in a job, shown in Figure 103 is to make possible the process of parameters inheritance. It applies the principles that customization requires the combination and arrangement of simple elements into more complex ones, in order to create a one-of-a-kind product that suits a specific need. The definition of hierarchy for parameters inheritance among Revit families mapped in Figure 105 is in line with Woodbury (2010) that stated that simple models of components are created and combined in more complex forms. Regarding folding and contouring, shown in Figure 58, Figure 59, and Figure 60, these are two out of five groups of digital techniques which according to Iwamoto (2009) have been the central component in many other manufacturing industries, for several decades, but not so in the AEC industry. Those experiments aimed to bridge the gap between a virtual BIM model in the design phase, and a physical component in the fabrication process. The process of exporting parameters from Revit is related to the following tasks from the proposed method shown in Figure 61.

According to Woodbury (2010), in parametric design, mastering computer programming is a skill that designers must have. This study recommends at least the basic knowledge in algorithms. In the evaluation of the first cycle of the research, it was identified as a lack of knowledge in writing algorithms among the members of the Small Production Cell. An introductory course on algorithms and computer programming was prepared by the researcher and ministered to the participants of the Small Production Cell. A summary of the course can be seen in Appendix I.

Figure 94 - Process of creating Libraries for kitchen cabinetry



Source: The author.

7.2.2. Second stage: Development

Custom-Drive Design: Creating libraries of BIM models by nesting

Nested families are families loaded into another family. This resource is very suited for customized products, but the complexity increases with the number of parameters. Moreover, it is necessary to create families with shared parameters. For example, rather than design a box from scratch, the same box can be created by the combination of families of gables, bottoms, tops, backs, doors, and drawers. When creating a nested family, the parameters can be shared or not shared. If parameters are not shared, the nested family appear in schedules as a single item. But with shared parameters, even though the nested family behaves as a single item, each component appears independently in the schedules. Revit families created in the second cycle had Shared parameters to be shown in schedule views. Drawers and Roll-Out-Shelves were families nested into cabinets and in order to get their parameters in Schedule and exported to the CNC, their parameters were created as Shared parameters.

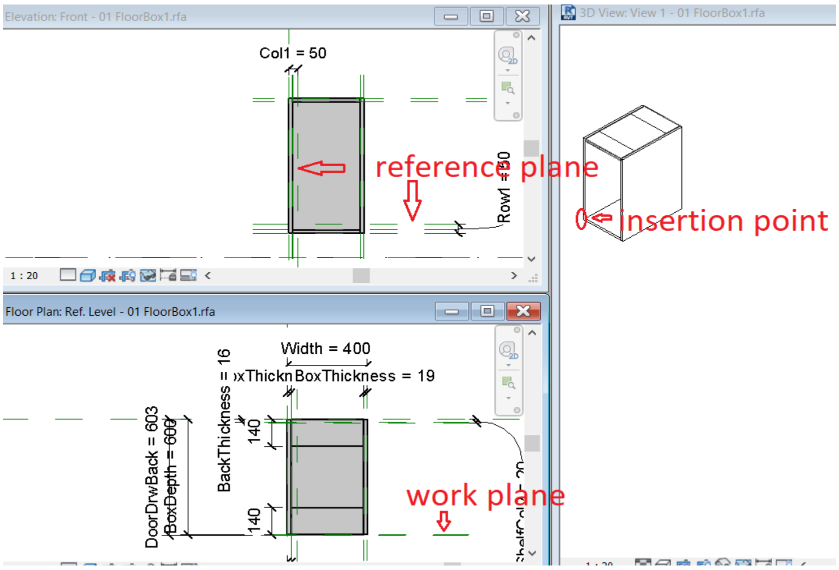
The process developed for creating libraries of BIM models for woodworking cabinetry is shown in Figure 94. The process is based on the technique of Nested families. There are four groups of families at the root level of this process. The Box Part Families group, the Drawer Part Families group, The Front Families group, and the Reference Plane Families. Table 24 lists some families that were created following the process described in Figure 94. The group of BoxParts has the families of left and right gables with the option to host hinges and a line boring for adjustable shelves. This group also has the families of bottoms with the option to have holes for legs and the family of backs. The group of families called Reference Planes contains the vertical and horizontal reference planes that are used to define the insertion points of the parts and to host the geometry. Figure 95 shows two reference planes in the Elevation view and the work plane in the Floor plan view and in the 3D View the intersection point can be seen. The parameters that define the relationships between the parts are associated with those reference planes. The group of drawer parts is the families of sides, bottoms, fronts and backs of the Drawer boxes that are afterward nested in a cabinet box. In the group called Front are the families of door and drawer options from the product’s catalog at the company. To a door, it is defined two, three, four or five hinges depending on its height. The group of

Box Families sets up the assembly relationship between parts. By setting up some parameters, Bottoms can be assembled between gables or on bottom of the gables. Tops can also be assembled between gables or on top of the gables, and backs can be assembled between gables, or on back of the gables or the cabinet may not have the back. Every box is a set of Left Gable, Right Gable, Bottom, Top, and Back. Besides these main parts, other parts can be added to the box, like fixed shelves, adjustable shelves, doors, tray dividers, drawers, and Roll-out-shelves. But each one of these parts can have several types.

The sketches in Figure 96 shows that gables can be of four different types that can be fabricated by Folding mitered or straight-cut panels. Figure 97 shows the fabrication detail for folding mitered panels, Figure 98 shows a sketch for assembling folding of straight-cut panels, and Figure 99 shows the sketch of the plan view of two cabinets assembled by nesting folded panels. One cabinet is assembled by nesting mitered folded panels and one cabinet is assembled by nesting the folded straight-cut panels. Gables fabricated by folding straight-cut panels are assembled by applying edge banding in the faces of the panels. These are just two examples of a very large number of possible combinations.

A BIM library for custom products requires frequent and in-depth changes due to the dynamic character of these products. Therefore, the creation and updating of BIM families were planned to follow a logical concept of morphological and parametric inheritance. This concept is exemplified in Figure 100. Initially, one cabinet family was created with the following parameters and constraints: A maximum height of 1100mm, and if the cabinet is less than 200 mm wide or less than 350 mm deep, it must have a full panel on top, otherwise, it must have two rails on the top. The rail width is constrained in 140mm. This family was used to create another family with the same parameters but different sets of constraints. Some parameters were changed, and the geometry related to the rails were erased. The height constraint for the new family would be no less than 1100mm height and will have a full panel at the top. And parameters were added to generate shelves. This inheritance logic makes it easier for the creation and updating of families in the library.

Figure 95 - Insertion point for a Base Cabinet



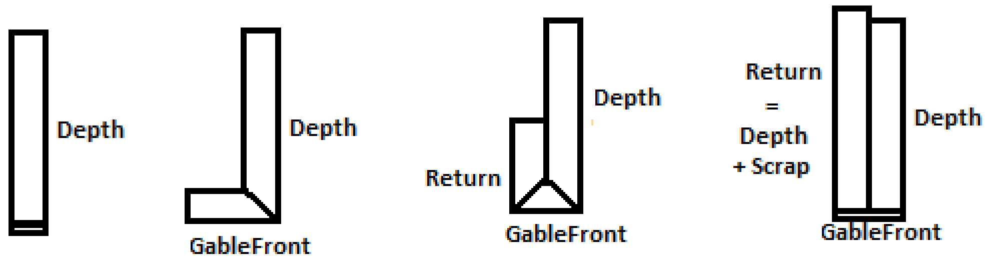
Source: The author.

Table 24 - Family samples from the Family library for Kitchen cabinetry

FAMILY LIBRARY	FAMILY SAMPLES
BoxPart	TallLeftHingeGableShelf, TallRightHingeGableShelf, Bottom, Back, …
Reference Plane	FloorBox5, FloorBox4, FloorBox3,…
Drawer Part	DrawerBottom, DrawerSide,…
Drawer	TandemBoxIntivo, TandemWoodDowel,…
Front	Door101, Door102,… Door150, Door151,…
Box	Tall 2Doors, Tall 1 Door Left Swing,…
Cabinet	Tall 2Doors, Tall 1 Door Left Swing,…
CabinetType	Tall 2Doors, Tall 2Doors ROS,… Tall 1 Door Left Swing, Tall 1 Door Left Swing ROS,…

Source: The author.

Figure 96 - Mitred-type gables

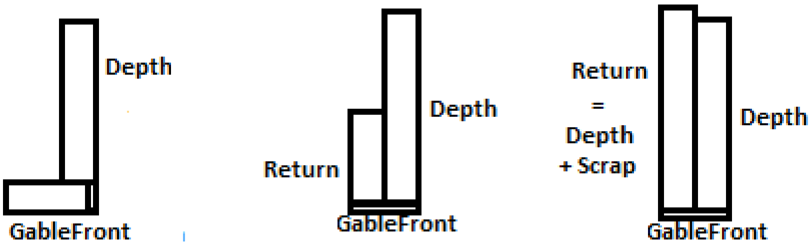


Source: The author.

Figure 97 - Fabrication detail for mitred gables, bottoms and shelves

Source: The author.

Figure 98 - Straight-cut type gables



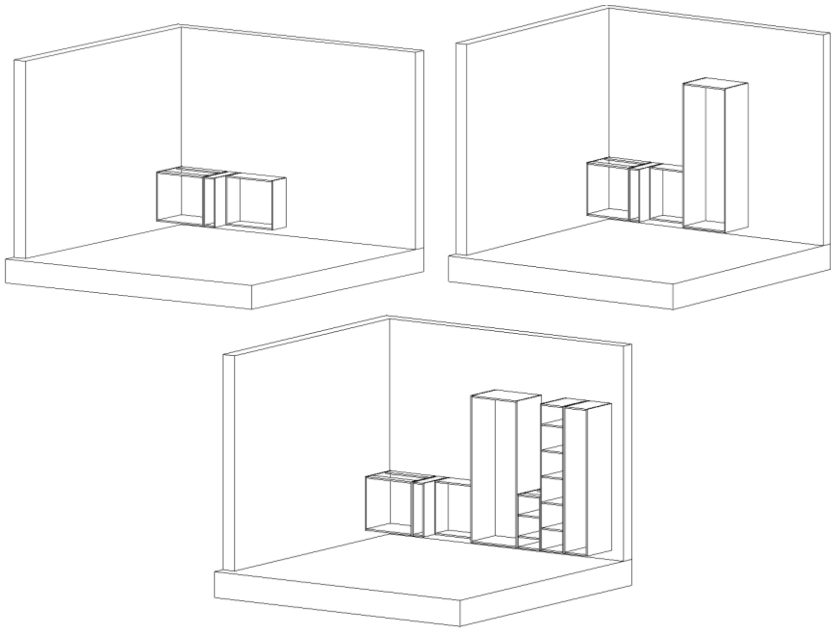
Source: The author.

Figure 99 - Two cabinets assembled with the gable families

Source: The author.

Creating libraries of BIM models is among the roles within a Small Production Cell, but the library is managed by a BIM manager. This is in line with what is prescribed by Semler (1993) (see Table 23), and the new skills, shown in Figure 65, which according to Woodbury (2010) are required from the designers especially relevant in the Mass Customization strategy. Moreover, the BIM Manager's role is to keep the link between several Small Production Cells in the context of complex and interdependent concepts (see Figure 55). When it comes to defining the BIM manager's role, there's not a set of rules that fit the needs of every company, but some roles were highlighted from what was observed in this research. In the context of Mass Customization, he manages small projects and must create patterns for the process in order to reduce redundancy and increase accuracy. The BIM Manager needs to be patient, listen to the users, lean on people to help him to perfect the templates, besides being skilled in every software the company and its associates works with. And not just the software. He must keep up with the BIM technology, know the company's business, be familiar with export formats, and coordinate a BIM model throughout its lifecycle. The BIM manager needs to have experience as a designer, be able to manage multiple projects at the same time, be aware of the information that must be attached to each model, and make sure that only the items used in most projects are kept in the library. The rest of the content must be easily accessible in a read-only place on the network because the library cannot be bogged down with all possible items.

Figure 100 - Conceptual logic for the creation of Components Library



Source: The author.

MC Adoption Strategy: Hierarchy of components within a job

Typical projects at the company may have more than one set of global variables. Figure 101 shows an example of a room with one single set of global variables. Figure 102 shows a room with two different sets of configurations, one configuration for components that sits on the floor, and a second configuration for the boxes that hang on the wall. Each configuration holds global variables for types of doors, drawers, and interior material.

Figure 101 - Room with one set of global variables

Source: The author.

Figure 102 - Room with two sets of global variables

Source: The author.

Figure 103 shows the Job partition adopted for transferring parameters from one cabinet to another. Applying the principle of hierarchy, used in computer science for Object-Oriented Programming, each job is partitioned in subdivisions called sections. Each section is subdivided into Assemblies. Each Assembly may contain Sub-Assemblies. Both an Assembly and a sub-Assembly are an arrangement of parts. The part is the elementary unit in the productive system. Each section has only one set of global variables, so a simple job can comprise only one section and a complex job can comprise two or more sections. Each section corresponds to a group of items called Assembly. Each Assembly is built on the shop floor and delivered as one unit. Assemblies that belong to the same section have the same characteristics, that is, they have the same global variables. Each Assembly is a collection of SubAssemblies or a collection of parts.

Figure 103 - Hierarchy of components in a job

Source: The author.

The SubAssemblies comprise the different types of drawers and Roll Out Shelves. In Figure 104, the lower sub-assembly part is called simply Drawer but the two parts in the upper part of the cabinet are called Roll Out Shelves. Each Sub assembly comprises one box and one mechanical track that slides the drawer or the Roll Out shelf. Drawers and Roll Out Shelves are called Sub assemblies because they are assembled to be a part of an item and because they inherit parameters from the item. The one drawer plus two Roll Out Shelves in Figure 104 are assembled in a box and they are considered a single item because they are sent preassembled to the client's site for the kitchen installation.

For each contract that is signed with a customer, it is generated a Job number. A contract can have multiple sections. Kitchen, bathroom, laundry, and bedroom are examples of sections. Each section has multiple Assemblies. An Assembly is a component that is transported as a unit to be installed on the job site. Sub-Assemblies are inserted inside Assemblies. One drawer and two Roll-Out-Shelves are shown in Figure 104 as examples of Sub-Assemblies. Not every Assembly has Sub-Assembly. Each assembly or subassembly is built from the combination of parts.

Figure 104 - One drawer and two roll out shelves nested in a box family

Source: The author.

In order to allow each part to be identified throughout the manufacturing and assembly process, a **label system** was developed containing the process intelligence. One label was generated by the Biesseworks software and attached on each piece that went out from the CNC machine. The label had an intelligent code that identified each piece, and information regarding the sequence of the process by which each piece should go through. The coding was created according to the subdivision of the job as shown in Table 25. The code has a 10-digit alphanumeric combination that associates each part within its job.

The **first four digits** identify the Job. The **fifth** and **sixth** digits identify the section. The **seventh** and **eighth** digits identify an Assembly. The **ninth** digit identifies a SubAssembly, and the **tenth** item identifies the Part; an elementary unit in the manufacturing process.

The **first** digit identifies the year. The letter A represents the year 2019, the letter B represents the year 2020, the letter C represents the year 2021 and so on. The **second**, **third** and **fourth** digits are numeric, which means that up to 1000 jobs can be run each year. This coding is structured according to the expected growth of the company. In 20 years, the company executed no more than 4000 jobs.

The **fifth** and **sixth** digits are an alphanumeric that identifies each section of a job. Each section is a set of Assemblies with the same technical specification. Section coding starts at A1 and goes to Z9 which means that each job can have up to 260 sections. Section coding is structured according to the expected growth of the company. The largest job performed so far had 52 Sections.

The **seventh** and **eighth** digits are an alphanumeric that identifies each Assembly within a Section. Assembly coding starts with A1 and goes to Z9 which means that each Section can have up to 260 Assemblies. Assembly coding is structured according to the expected growth of the company. The largest Section performed so far had 83 Assemblies.

The **ninth** and **tenth** digits identify each SubAssembly within an Assembly and each Part within a SubAssembly. It starts with A and goes to Z which means that each Assembly can have up to 26 SubAssemblies and each

SubAssembly can have up to 26 Parts. This coding is also structured to the expected growth of the company.

Table 25 - Code linked to each part in the manufacturing process

Job	Section	Assembly	SubAssembly	Part
A001	A1	A1	A	A
A002	A2	A2	B	B
A003	A3	A3	C	C
...	...	...		...
Z999	Z9	Z9	Z	Z

Source: The author.

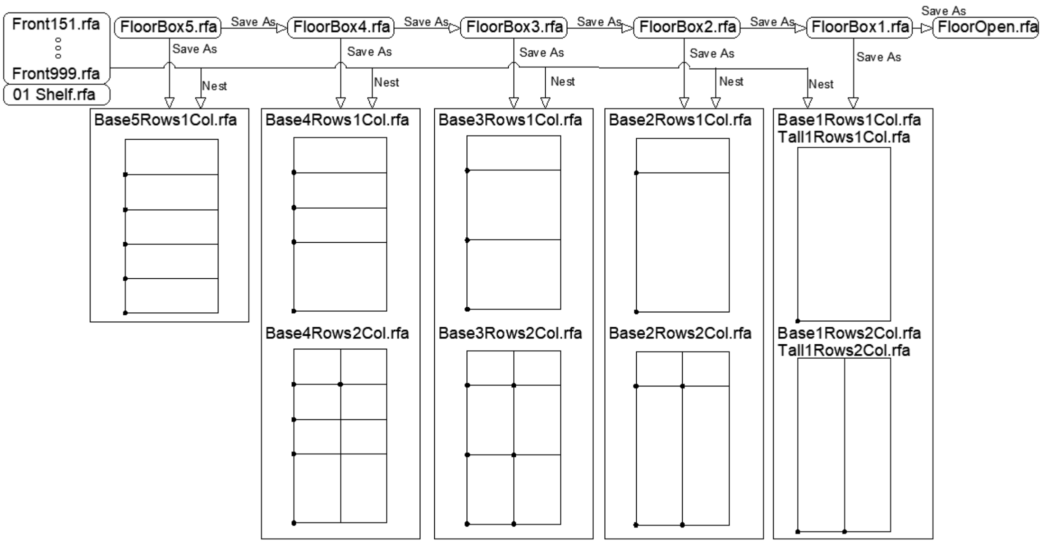
BIM Toward Fabrication: Parameters inheritance

For the definition of hierarchy for parameters inheritance among Revit families it was applied an–approach that consisted in creating the model of a more complex component, and from this model create other simpler models through the process of eliminating unnecessary parameters and changing values and formulas relative to the remaining parameters in the new model.

Due to the great variability between products in an industry of customized products, it is impossible to reach a point where the library can be said to be complete. Changes in existing components and the creation of new components are continuous work. Therefore, to make it easier to maintain the Revit library of the company, the principle of hierarchy among components was adopted. Components were created based on parameter inheritance. According to this principle, each created family, inherited the geometry, the parameters, and the constraints of its parent family.

In order to illustrate this principle, Figure 105 shows the sequence of creation of box families. The first family is named *FloorBox5*. This family has five horizontal reference planes, whose intercessions with a vertical plane at the leftmost side give rise to five points of intercession. The *FloorBox5* family is used to generate the *Base5Rows1Col* family. *Base5Rows1Col* has five drawers as wide as the cabinet. The *FloorBox4* family is created from the *FloorBox5* family. One of the horizontal reference planes is deleted, a vertical plane is created in the center, and some parameters have their formulas changed. Then *FloorBox4* family is used to generate the *Base4Rows1Col* family that has four cabinet-width drawers, as well as the *Base4Rows2Col* family that has insertion points for four cabinet-width drawers or for split-drawers. The family called *FloorBox3* is created from the *FloorBox4* family. One of the horizontal reference planes is deleted, a vertical plane is created in the center, and some parameters have their formulas changed. Then *FloorBox3* family is used to generate the *Base3Rows1Col* family that has three cabinet-width drawers, as well as the *Base3Rows2Col* family that has insertion points for three cabinet-width drawers or for split-drawers. The process repeats until the *FloorBox1* family is generated. This family has only one insertion point. This process of creating families for the library was created based on the principle of parameter inheritance in descending order because the process of eliminating parameters to generate the new family is less error-prone than creating new parameters and reference planes each time a new family is generated.

Figure 105 - Hierarchy and Parameters inheritance among families

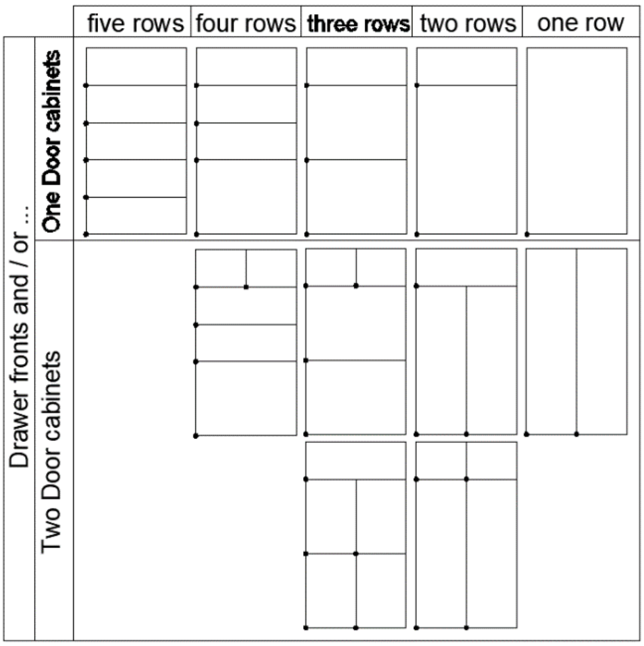


Source: The author.

The logic used to plan and develop the Revit library containing the 141 products of the catalog of the company followed the general concept of inheritance of parameters and the hierarchy principle used in object-oriented programming. For the creation of this library, the Revit *Generic Model.rfa* template was chosen. This template is under the Component Category.

Figure 106 shows a sketch of how those 141 components were consolidated into 11 groups of families based on the Reference Planes they require. Five groups have two vertical reference planes and six groups have three reference planes. For nesting doors and drawers into cabinets, it was taken the intersection between one vertical and one horizontal Reference Plane in a given work plane. The intersection between those three planes is the insertion point for the family. By the combination of two vertical Reference Planes, five horizontal Reference Planes, and the plane at the back of the Doors as the Work Plane, it was possible to define the insertion point for any door or drawer nested in each cabinet from the catalog. The black dots are the insertion points. All families have the same parameters but different formulas for locating the reference planes.

Figure 106 - Reference planes for nesting doors and drawers into cabinets



Source: The author.

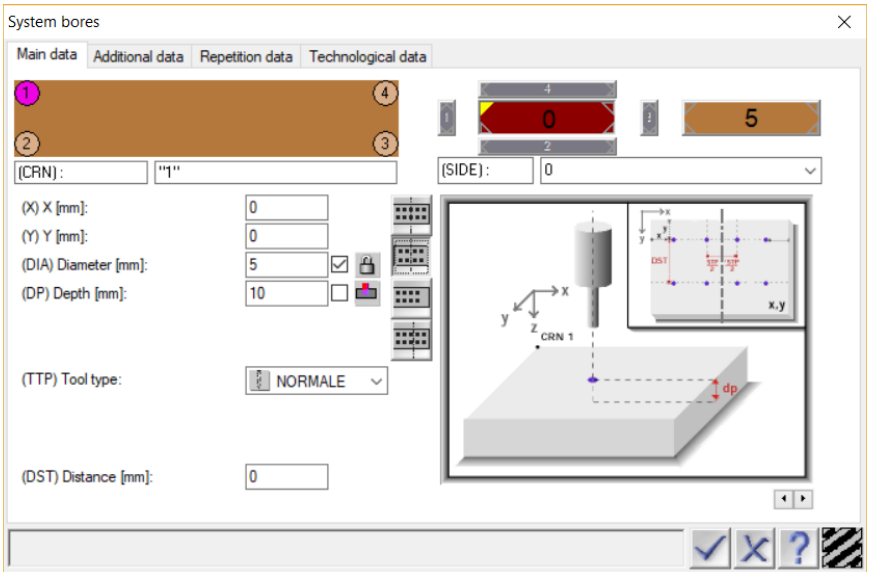
Digital Fabrication in MC: Fabrication techniques and Plant Layout

In order to better perform the experiments with Folding and Contouring, the chosen Digital Fabrication techniques, the researcher attended a Biesseworks course, the native language of the two-and-a-half axis CNC machine[29] used in the digital manufacturing. The course was divided into two modules: the first consisted of the machine configuration, operation, programming and exporting and importing text files and STL and SAT geometry

[29] Rover Skill 15.36 G FT BIESSE ARTECH

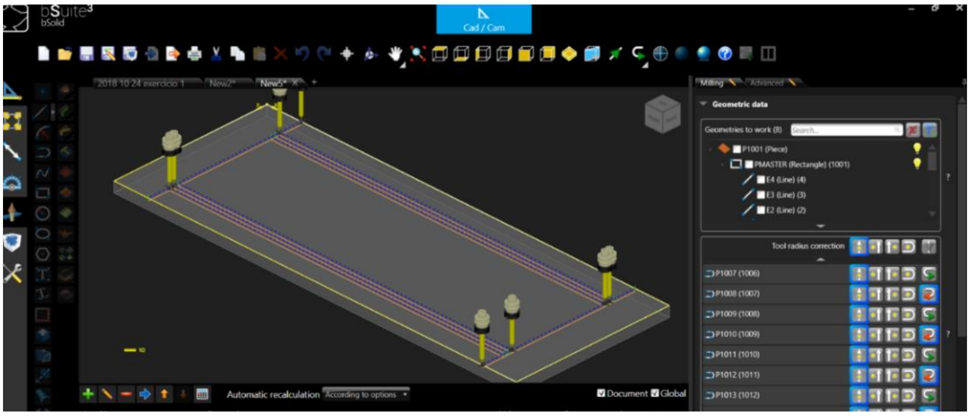
files. The second consisted of simulation of fabrication followed by the actual fabrication of a door. Figure 107 shows the programming environment and Figure 108 shows the simulation environment. In the configuration environment, the parameters of the machine operation are defined like tools, speeds, and tool compensation. Some parameters are pre-defined by the manufacturer such as tool speed. Other parameters are subject to several factors. For example, the milling feed rate is based on tool dimensions, material type, and tool speed. Settings should be performed very carefully because if not, both the machine and tools can be damaged. There are some tasks in the programming environment that are straightforward like the creation of vertical boring, routing straight lines, and even drilling a series of holes. But there are some other more complex tasks like routing circles and arcs. These run clockwise or counterclockwise, and if not accurately programmed, dangerous results may occur.

Figure 107 - Biesseworks software Programming environment



Source: The author.

Figure 108 - CNC simulation of the fabrication of a door



Source: The author.

Figure 109 shows an example of a box fabricated by Folding. This technique turns a mitered flat surface into a three-dimensional box or drawer. Folding was used also to design and fabricate fascias and valances for the kitchen finishings. Figure 110 shows an example of doors fabricated by Contouring. This technique is a subtractive process of creating a three-dimensional object by removing successive layers of material from a surface.

Figure 109 - Mitred Folding technique

Source: The author.

Figure 110 - Doors created by Contouring technique

Source: The author.

During the fabrication experiments, it was observed that the manufacturing plant layout in the company, has a linear configuration that is well fitted for Mass Production but not for a Mass Customization environment. Due to the fact that in Mass Customization each product is unique, a linear configuration, which is efficient in Mass Production, causes bottlenecks in the production system and excessive flow of material. This flow does not add value to the product and should be avoided.

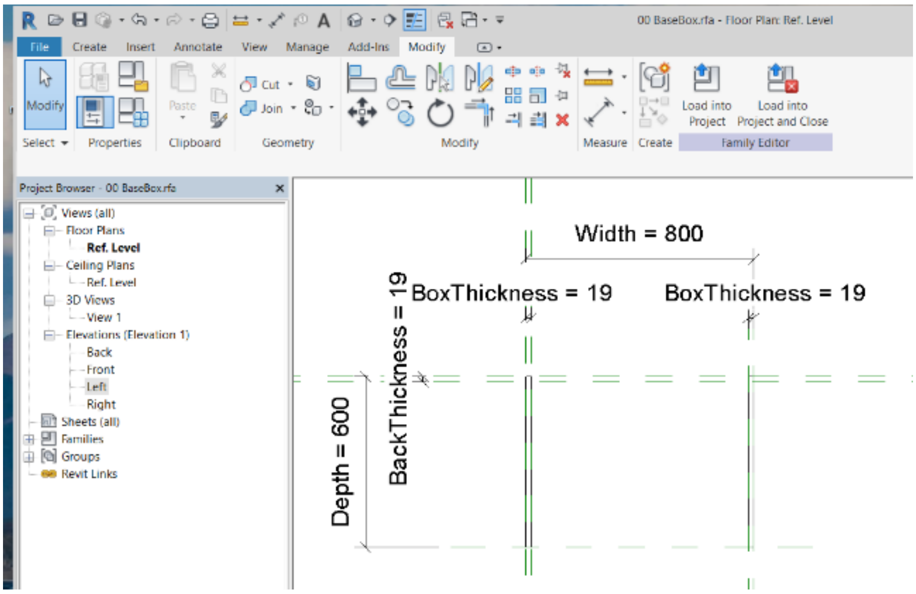
It was suggested to the company, to change the manufacturing plant layout to a topology with the assembly area in the center, which would reduce the material flow that does not add value to the product and decrease the incidence of bottlenecks in the production system. The configuration of space allowed to each section would become dynamic, changing according to the characteristics of each product. This suggestion is in line with the Process Flexibility required for Mass Customization as shown in Figure 53. The suggested topology is due to the fact that the production flow in Mass Customization is neither uniform nor predictable. Each job has a distinct flow. When a piece comes out of the CNC milling machine, it can go to the edge banding machine or to the painting booth, or to the assembly section or go directly to the delivery section where they are checked, classified and sent to the client's site. Jobs are delivered in clusters according to the logistics of the final installation. When a piece comes out of the edge banding machine, it can go to the assembly section or to the delivery section. After painting, a piece can go to the assembly section or to the delivery section. The cost of changing the manufacturing plant layout according to the suggested layout would be high because the plant is a complex of heavy machinery, with a net of piping for exhaustion systems and compressed air for machines and workstations. But a few small changes were made by changing the location of some small machines, and a reasonable improvement in the flow of production was achieved.

Exporting parameters through Dynamo

The families in the second cycle were created following the Process to Create a Family described in the first cycle but had more intelligence embedded in the parameters. A generic family was created with parameters and reference planes created specifically to allow the hosting of drawers, doors or shelves. This family had three vertical reference planes and six horizontal reference planes. The intersection of these planes with a working plane orthogonal to all other planes defined the insertion points for nesting the families of drawers, doors or shelves.

The Revit template chosen was the Metric Generic Model.rft family template. The intersection between Center (Front/Back) and Center (Left/Right) Reference Planes was chosen to be the insertion point of the box in the project. Figure 111 shows some reference planes created to host the geometry. Parameters were created and related to the dimensions placed at the reference planes. As the geometry of the panels was being added, they were locked to the reference planes and then turn hidden, so that no geometry would be associated with geometry, but rather with reference plans. Each action was followed by tests to verify the behavior of the reference planes, and if the parameters and constraints were changing as planned. Parameters were created as Instance parameters, that is, when loaded into a project, changes made in the value of a parameter affects only that instance of the family.

Figure 111 - Reference planes and parameters for the “BaseBox” family



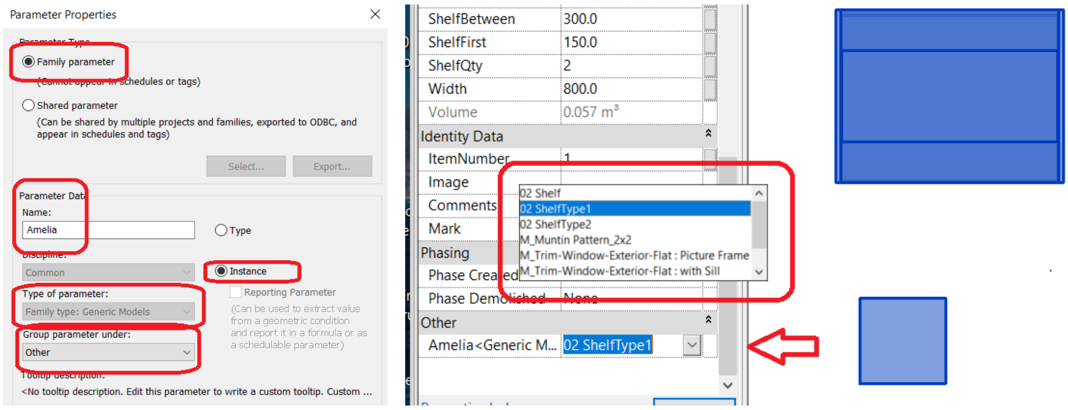
Source: The author.

The experiment with nested families was carried out by inserting doors, shelves, and drawers into a family of a box that served as the host. Parameters were created in the host family and associated with the geometries of doors or shelves or drawers. Figure 112 shows a Customized drawer nested in an under-sink cabinet and Figure 113 shows a dropdown in the Project Browser of a host family. In it appears all families of the same type of families that had been nested. (in this case, Generic Models). When the nested family was inserted into a project, by changing a parameter, all geometries associated with that parameter also changed. Each parameter changed the geometry associated with it.

Figure 112 - Drawer nested in an undersink cabinet

Source: The author.

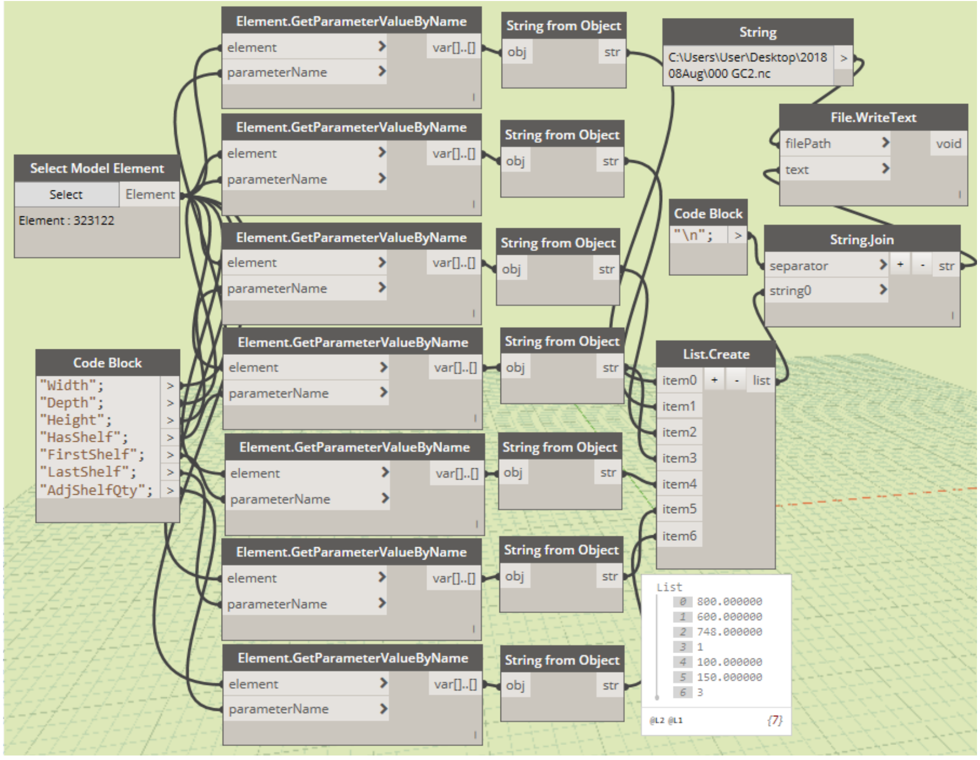
Figure 113 - Nesting shelves into a cabinet box



Source: The author.

Dynamo's visual programming was used to export Revit parameters through text files to the CNC BiesseWorks software, and to generate a list of specification of hardware to generate purchase orders. In the visual programming environment of Dynamo, a node called ExcelWriteToFile was used to create the text files. This node has six inputs: filePath, SheetName, StartRow, StartCol, Data, and OverWrite. The **filePath** input is the path where Dynamo places the created excel file. This input was connected to another node called “File Path” that acts as a placeholder for a blank Excel file workbook. The “**SheetName”** input was linked to a “Code Block” node that provided a string with the name of the Excel sheet within that blank Excel file workbook referenced in the first input of the ExcelWriteToFile node. The default is usually “Sheet1”. The “**StartRow”** input and the “**StartCol”** input are respectively the starting row and column for the first cell to be placed data from Revit to the Excel sheet. The “**OverWrite”** input is a yes/no input type that tells whether to overwrite the existing values in the Excel sheet. Initially, a blank file was created in Excel as the primary file for storing the Revit data. Then the Run option in Dynamo was set to “Manual”, to begin adding nodes. The “**File Path**” node was added and connected to the “**FilePath**” input of the ExcelWriteToFile node. After that, by clicking the “Browse…” button a navigation window was opened to navigate to the excel file that had been created. As shown in Figure 114, the "**Select model Element**" node was used to identify the model component that the data would be extracted from. Strings with the parameter names to be exported were supplied through the "**Code Block**" node. The parameter values were obtained with the node "**Element.GetParameterValueByName**". The values were transformed into strings and used to create an array. From this array, data was exported to a text file.

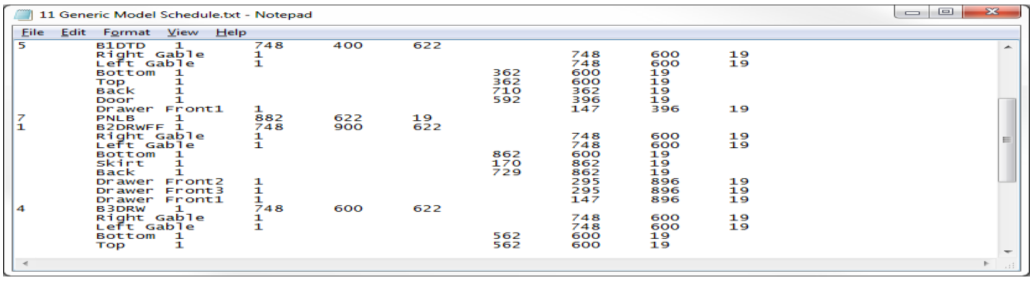
Figure 114 - Exporting parameters from Revit to text files through Dynamo



Source: The author.

The machines used for Digital Fabrication in the experiment were connected to the design computers through the web. Parameters from the BIM models were exported to the CNC machines through the web. Figure 115 shows a text file that was exported from Revit.

Figure 115 - Text file exported from a Revit Schedule view



```
11 Generic Model Schedule.txt - Notepad
File  Edit  Format  View  Help
5       B1DTD   1       748     400     622
        Right Gable     1                       748     600     19
        Left Gable      1                       748     600     19
        Bottom  1                       362     600     19
        Top     1                       362     600     19
        Back    1                       710     362     19
        Door    1                       592     396     19
        Drawer Front1   1                       147     396     19
7       PNLB    1       882     622     19
1       B2DRWFF 1       748     900     622
        Right Gable     1                       748     600     19
        Left Gable      1                       748     600     19
        Bottom  1                       862     600     19
        Skirt   1                       170     862     19
        Back    1                       729     862     19
        Drawer Front2   1                       295     896     19
        Drawer Front3   1                       295     896     19
        Drawer Front1   1                       147     896     19
4       B3DRW   1       748     600     622
        Right Gable     1                       748     600     19
        Left Gable      1                       748     600     19
        Bottom  1                       562     600     19
        Top     1                       562     600     19
```

Source: The author.

7.2.3. Third stage: Evaluation

The process developed for creating libraries of BIM models for woodworking cabinetry was based on the technique of nested families. The creation of parts of cabinets using patterns helped to break a complex body into simpler components. Moreover, this inheritance logic made it easier for the creation and updating of families in the library.

The hierarchy of components in a job, made possible the process of parameters inheritance. It applied the principles that customization requires the combination and arrangement of simple elements into more complex ones, in order to create a product that suits a specific need. Partitioning a job allowed parameters to be transferred from one cabinet to another and simplified the creation of complex cabinets with nested drawers or roll-out-shelves. The creation of a label system was essential for the identification of each part during the manufacturing process and in the delivery phase.

The definition of hierarchy for parameters inheritance among Revit families allowed the creation of simpler templates derived from more complex forms. The approach taken to create a more complex model and from this model generate other more simplified, by eliminating some reference planes and parameters and changing values and formulas relative to the remaining parameters showed to be less error-prone than the reverse approach, which is creating a simpler module and from it, generate a more complex module by adding new reference planes and parameters.

Regarding the experiments with digital fabrication, the results helped to bridge the gap between a virtual BIM model in the design phase, and a physical component in the fabrication process. It was observed that designers should exchange information with the CNC machine programmer at the design stage to facilitate not only the machine programming but the setup and operation. The collaboration between those two specialists is necessary because it affects the CNC machine setting process which must be performed as carefully as the fabrication programming, and because a simulation must be carried out each time a program is created or edited, before the real fabrication to prevent damages to the machine.

Dynamo's visual programming was used to export Revit parameters through text files to the CNC BiesseWorks software, and to generate a list of specification of hardware to generate purchase orders. But the transition from the current system based on spreadsheets to BIM modeling and web database application had but small progress in the second cycle. The Small Production Cell participants started expressing little commitment to the MC implantation process.

7.2.4. Fourth stage: Reflection

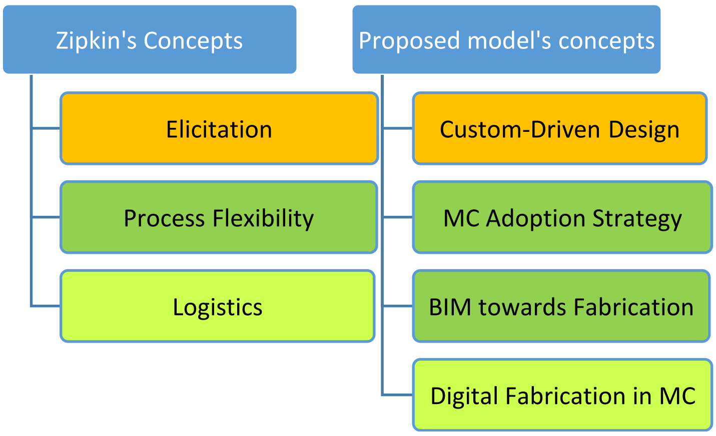
This stage expressed the lessons learned in the second cycle. The summary of lessons learned is: (1) The implementation of the method has an impact on people as strong as it is on processes; (2) Implement MC is not to automate existing processes. It is to create new workflows and new processes; (3) Web database applications can enhance the application of BIM models in MC manufacturing, but a successful MC implementation must be a thorough plan that gets the staff involved and committed from the very beginning and throughout the whole process; (4) The manufacturing plant layout in a Mass Customization environment, can not have a configuration similar to that a Mass Production system. Because in Mass Customization each product is unique, a linear configuration, which is efficient in Mass Production, causes bottlenecks in the production system and excessive flow of material.

8. CLARIFICATION OF LEARNING ACHIEVED

The output at this step is the explicit identification of the elements that positively contributed to the generation of theoretical or practical knowledge and the elements that failed. The achievements and factors of success as well as the unsuccessful points and failures and the knowledge generated, both theoretical and practical are declared. The aim is to ensure that the research serves as a reference and aid for the generation of knowledge, both theoretical and practical.

It was found that the proposed model in this research accomplished solutions for the Mass Customization limits and cautiousness identified by Zipkin (2001). This was characterized as one of the theoretical contributions of this work. As illustrated in Figure 116, the Custom-Driven Design brought an efficient system for interaction with the client, which was a challenge in the Elicitation element of Zipkin. The combination of the concept of Small Production Cell, which was adapted from Semler (1993), the application of the concept of Object-Oriented Programming (OOP) to the creation of libraries of BIM models and the process to create Revit families adapted from Aubin (2011), allowed to achieve the Process Flexibility prescribed by Zipkin. The information inheritance, the labeling system, and the shop floor plant layout within the concept of Digital Fabrication in MC performed the Logistics' requirements of Zipkin. These were significant theoretical contributions.

Figure 116 - Interaction between Zipkin's concepts and the proposed Model



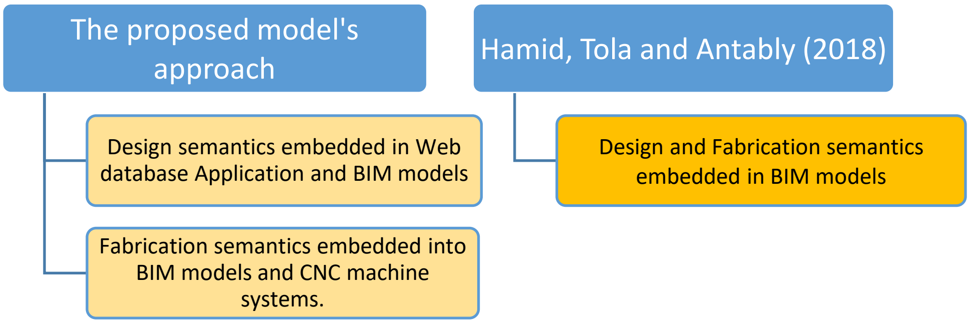
Source: The author.

The Small Production Cell must act as a Small Company inside a bigger company that will nurture it until it matures and is ready to split in two, as illustrated in Figure 64. After that, the company has two Small Production Cells and the BIM Manager who begins to play the role of making these two independent units work collaboratively. This concept is one important theoretical and practical contribution of this research, though it was accomplished only partially in the experiment, due to the fact that the time required for a Small Production Cell to be mature and ready to be divided into two, showed to be more than the time available for the research.

The process of creating BIM models for the component library, and the process of partitioning a job into subdivisions, which came from concepts adapted from Woodbury (2010), through the application of the principle of Object-Oriented Programming, can both be considered important theoretical and practical contributions of this research, though they were accomplished only partially in the experiment, due to the fact that it was necessary a significant time for participants getting skilled with algorithm creation and computer programming.

In the proposed model, the semantics of the Design and Fabrication processes are distributed in three systems: Web database application, BIM models and CNC machine applications. As shown in Figure 117 the Design semantics are embedded into a Relational Database and into BIM models, and the Fabrication knowledge is embedded into BIM models and into the software that the CNC machine manufacturer provides. This approach provided the creation of systems having low coupling, high cohesion and security for the intellectual capital of the company. Likewise, this was characterized as one of the theoretical contributions of this work in relation to the approach of Hamid, Tola, and Antably (2018) that embedded both Design and Fabrication semantics in BIM models.

Figure 117 - Interaction between Hamid's concepts and the proposed Model



Source: The author.

The proposed model's approach contributed to solving the challenges faced by Hamid, Tolba, and Antably (2018) described in chapter 5 (Systematic Literature Review). (1) The knowledge embedded in a database provided security for the company's intellectual capital. (2) It was provided an environment for the creation of systems with low coupling and high cohesion, which means, low degree of interdependency between modules and high degree to which all parameters directed toward performing a single task are contained in a single function. (3) Portability for BIM models: BIM models can be used more easily on different CNC machines because the operating information is incorporated into the software that the CNC machine manufacturer provides. (4) Interoperability through text files instead of DXF files gives more freedom for parameterization, which is a great benefit because the quantity and complexity of parameters in an Engineered-To-Order environment are very large.

With regard the impacts of the adoption of BIM in Processes, Skills and Fabrication for Mass Customization in the context of Engineered-To-Order manufacturing, the contribution of this research is related to some of the Critical Success Factors used to measure a successful BIM implementation identified by Antwi-afari et al. (2018) as further described.

Impacts on Processes: A Small Production Cells acting from design to fabrication, enhances the exchange of information, the collaboration among stakeholders, and ensures effective communication among project participants. The Schematic BIM Library containing parameters imported from the web database application allows the verification of consistency to the design intent. The geometric semantics embedded in the Production BIM Library provides also shop drawings besides fabrication parameters.

Impacts on Skills can be illustrated in Figure 65 which relates the new skills required from the designers with the new strategies offered to them. The combination of those new skills and strategies are useful to provide BIM models for offsite prefabrication and to get less reworking and fewer document errors and omissions through accuracy and reliability of data provided by the Web Database Application.

Impacts on Fabrication can be highlighted with the fact that the participation of clients in the design stage through the web database application containing semantics for parameterization of the BIM models, provides the balance between the freedom given in the parameterization and the constraints required from the fabrication process. This balance enhances the exchange of information and knowledge management. Another contribution is related to the use of patterns in the creation of components library providing BIM models for fabrication.

8.1. Generalization

Light-frame structure construction uses a combination of structural components in floors, walls and roofs. Liu et al. (2018) proposed a rule-based automated BIM approach for designing a light-frame residential building. The proposed artifacts in this research can be applied to the automated design and offsite fabrication and modular construction of light-frame residential building aiming at mass customization.

Multi-trade prefabrication is the process of fabricating mechanical, Electrical and plumbing (MEP) components in the form of clusters of racks. Specialized MEP crews build the racks off-site. Then, the racks are delivered to the job-site, lifted to their proper floors and installed. Jang and Lee (2018) investigated the causes of contradicting results regarding the benefits of Multi-trade prefabrication based on BIM. They concluded that coordinating MEP systems took longer in a Multi-trade prefabrication process and the selection of projects were critical for the successful implementation of BIM-based Multi-trade prefabrication. The proposed artifacts in this research can be applied to BIM-based Multi-trade prefabrication to enhance the coordination of various systems in the same space.

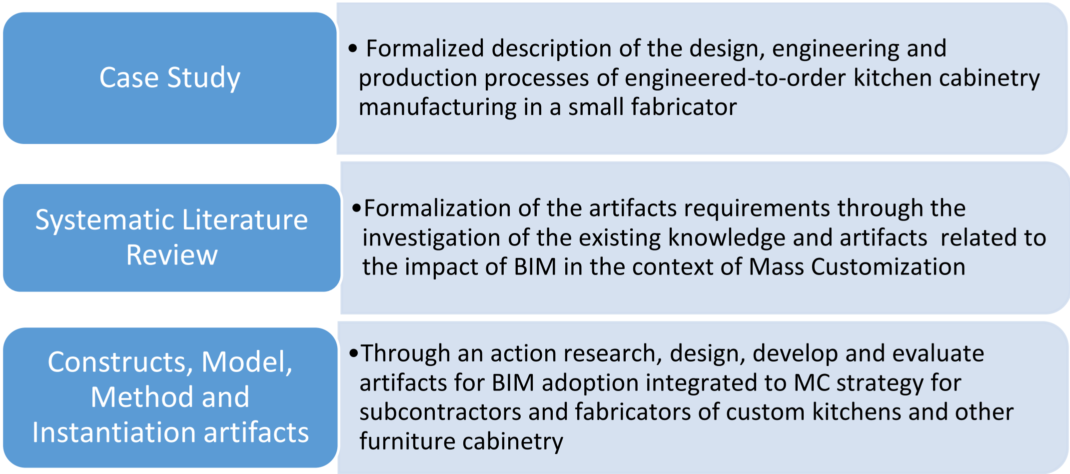
9. CONCLUSIONS

In this chapter, it is presented the final discussions about the topic addressed in the context of the research, the paths, and processes necessary for the creation, development, and feasibility of the proposed artifacts. Besides the formalization of the results and decisions made during the research, the outputs at this step report the research limitations, and offer some insights by the researcher, as they can lead to new problems and guide in future works. The great contribution of this research is the detailing of the complete process of incorporation of BIM to the design and manufacturing of Engineered-To-Order building components.

The practical problems referred to in the first chapter (Introduction) were: (1) Low productivity in the design detailing process for Digital Manufacturing in the Mass Customization context at woodworking industry; (2) Lack of knowledge of BIM impact in Digital Manufacturing in the context of Mass Customization; (3) Lack of knowledge in implementing BIM in small businesses, more specifically in design and manufacturing of customized engineered-to-order products; (4) Lack of integration among sales, marketing, basic conceptual design, detailing engineering design and production. Based on these problems, one general objective and three specific objectives were defined for this investigation. The three specific objectives corresponded to the outputs shown in Figure 118. The degree of fulfillment of the objectives and the contributions and limitations of the research are discussed in this chapter.

The first output of the research was the case study which provided a formalized description of the design, engineering and production processes of engineered-to-order kitchen cabinetry manufacturing within a typical Small-and-Medium-Enterprise (SME) and identified some of the typical problems faced by engineered-to-order components fabricators which comprised the problems addressed in this research. This research objective was facilitated by the previous experience of the researcher in this sector of the AEC industry.

Figure 118 - Correspondence between research outputs and research objectives



Source: The author.

The second specific objective was accomplished through the Systematic Literature Review (SLR) that conducted the formalization of the artifacts' requirements through the investigation of the existing knowledge and artifacts related to the impact of BIM in the context of Mass Customization. Among the studies considered relevant to the research, the most influential in the artifacts proposal were: (1) Poirier Staub-French and Forgues (2015) which stated that BIM implementation in Small-and-Medium-Enterprises requires a clear strategy; (2) Khalili and Kolarevic (2016) which stated that true customization requires the participation of customers in the design stage; (3) Goulding, Rahimian, and Wang (2014) which suggested web-based platforms for sharing information; and (4) Farr, Piroozfar, and Robinson (2014) who presented the concepts of subdivision of a complex body into simpler parts. The outputs from the SLR were useful for the artifacts' proposal.

The accomplishment of the third specific objective which was the design, development, and evaluation of Constructs, Model, Method and Instantiation artifacts for BIM adoption integrated to MC strategy for subcontractors and fabricators of Engineered-To-Order cabinetry, are related to providing knowledge for the reduction of research problems under the aspects described in the next few paragraphs.

The flexibility of the production system was provided by collaboration between design and fabrication specialists within the Small Production Cell. The method prescribes that after a Small Production Cell is consolidated, it must split, generating other Small Production Cell. The full functionality of the Small Production Cell requires a time of maturation beyond the time span of this research. Nevertheless, the Small Production Cell enhanced the productivity in the design detailing for Digital Manufacturing in the Mass Customization context at the woodworking industry.

The Small Production Cell acting independently is efficient in the design, fabrication and assembly phases in the manufacturing system. Through the Small Production Cell, the production system becomes more flexible and interaction with clients turns to be more efficient.

The process of embedding fabrication geometric semantics into BIM models and fabrication semantics into the CNC machine systems contributed to the knowledge of BIM impact in Digital Manufacturing in the context of Mass Customization. Incorporating design specification semantics and variable constraints into databases not only supports the workflow between design and manufacturing but also provides security to the company's intellectual capital.

The use of patterns and the application of Object-Oriented Programming concepts facilitated the creation of the BIM models library. Though the facilitation of the frequent updates of a library in a Mass Customization strategy could not be investigated due to the facts that this requires a long time of maturation, the results provided knowledge in implementing BIM in small businesses, more specifically in design and manufacturing of engineered-to-order products.

Design parameters embedded in the web database application provided the environment to handle the high quantity of parameters, the complexity of the rules, and the interdependent relationships in a Mass Customization strategy. This solution can enhance the integration among sales, marketing, basic conceptual design, detailing engineering design and production. The design semantics embedded into a Relational Database and into BIM models, and the fabrication semantics embedded into BIM models and into the software that the CNC machine manufacturer provides, allowed not only a solution for the challenges faced by Hamid, Tolba and Antably (2018), but also solutions to two of the research problems: The lack of knowledge of BIM impact in Digital Manufacturing in the context of Mass Customization, and the lack of knowledge in implementing BIM in small businesses, more specifically in design and manufacturing of engineered-to-order products.

One of the barriers to interoperability is the complexity of controllers in CNC machines. This barrier can be mitigated by incorporating manufacturing semantics into the database.

One of the research problems that aroused the researcher’s interest in finding solutions to practical problems faced by engineered-to-order component manufacturers was the Lack of knowledge of BIM’s impact on Digital Manufacturing in the context of Mass Customization. One contribution of this research is to provide knowledge into the impacts of the adoption of BIM on Processes, Required Skills and Fabrication, for the manufacture of Engineered-To-Order components in the context of Mass Customization, as further described. The observed impacts were: (1) Breaking a complex component into simple components according to predefined constraints related to fabrication, gives way to the process of creating BIM libraries as illustrated in Figure 94; (2) The elicitation through web database application containing constraints for code compliance from regulatory bodies of the construction industry, parameters for authoring the BIM Models and for fabrication, provides accuracy and reliability of data leading to less reworking and fewer document errors and omissions; (3) The Small Production Cell acts like a small company inside a bigger company that will nurture it until it matures and is ready to split in two or three, as illustrated in Figure 64. This policy enhances collaboration among design and fabrication stakeholders.

The hierarchy of components in a job makes possible the process of parameters inheritance through the combination and arrangement of simple elements into more complex ones. The observed impacts on Required Skills were: (1) The knowledge of basic mathematical concepts of geometry, as well as

Object-Oriented Programming concepts, and Data structures, are skills required to the creation of BIM models toward fabrication. These skills enable the designers to verify the consistency of the BIM model to the design intent and provide effective communication among project participants and (2) the rotation of roles within a Small Production Cell allows the designer to have competence in fabrication and the fabricator to have competence in design. This practice enhances collaboration among those involved in design and fabrication, which is one of the Critical Success Factors of implementation of BIM identified by Antwi-afari et al. (2018).

The observed impacts on Fabrication were: (1) The Small Production Cell, a group of at least two specialists, one in design and one in manufacturing uses BIM Models and database application to blend design intent to fabrication constraints as illustrated in Figure 57. The Small Production Cell ensures effective communication and enhances collaboration between designers and fabricators. Those are Critical Success Factors (CSF) of BIM implementation identified by Antwi-afari et al. (2018); (2) Implementing hierarchy and parameters inheritance in creating Revit families as shown in Figure 105 provided BIM models for fabrication, which is also a CSF in the classification of Antwi-Afari; (3) Parametric design with components nested according to pre-defined rules and constraints met the requirements of Eastman et al. (2008) for BIM toward fabrication.

When customer's requirements are controlled by a database application associated to parameters from BIM models, the apparently conflicting issues between the value placed on a level of customization by the customer's requirements, and the system's ability to deliver that level of customization, can be combined to achieve Mass Customization. The level of Mass Customization that can be achieved is related to the degree of relation between the parameters in the BIM Model and the variables from the database application, which also provides security to the intellectual capital of the company.

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Appendix A - Selected Primary Studies

Reference	**AHN et al (2016)**	**ANIL, UNAL and KURC (2012)**	**BARAK Et al. (2009)**
code	26C61b23	096 c61b 106	078 c61b 24
ARTIFACT	Description of organizational structures to maximize the benefits of BIM adoption	MODEL: Description of requirements for simultaneous design and detailing of reinforced concrete frames; INSTANTIATION: Validation of the Information Requirements Model for simultaneous design and detailing of reinforced concrete frames	A representation of specific requirements of BIM systems for cast-in-Place Reinforced Concrete Structures
Artifact type	Model	Model and instantiation	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	The most important areas where BIM has been implemented are MEP coordination, visualization, communication, marketing and site logistics / Challenging in reorganizing the company to take full benefits of BIM adoption. Organizational practice and transformation to enable to maximize the benefits and minimize the problems due to BIM adoption		Although productivity gains have been demonstrated in research settings BIM tools are not sufficiently mature to support widespread production use of Cast-in-Place Reinforced Concrete
HEURISTIC (Contingencial / Constructive)	The construction industry needs to develop a better understanding of how BIM can effectively integrate functions such as energy simulation, estimating, facility management and operation simulation /		

	The research findings are beneficial for medium-size construction industry who have a market in commercial offices, education, hospitals and multiresidential projects		
Context:	BIM	BIM	BIM
Benefit	LIFECYCLE INTEGRATION:This study describes the organizational structure to maximize BIM inplementation throughout the project lifecycle	INTEROPERABILITY: The study proposes and tests the applicability of a design and detailing of reinforced concrete frames model that allows flexibility in handling detailing tasks directly in the design	LIFECYCLE INTEGRATION: Description of requirements for a BIM tool for cast-in-place reinforced concrete that provides stakeholders with better modeling and management from the early conceptual stages through detailing and up to maintenance
STAKEHOLDER:	Contractors	Architect / Engineer	Contractors
TOOLS: SOFTWARE / HARDWARE		XML web services; Graphical User Interface: C#.net; structural analysis: ETABS v9.5	Georgia Tech process to product modelling GTPPM tool
Application:	Construction components	Construction components	Construction components
Research center	Hanyang University, Korea; George Washington University, USA	Middle East Technical University, Turkey	Technion-Israel Institute of Technology, Israel; Georgia Institute of Technology, USA
Research methods	Case study	Modeling *; Case Study	Modeling *
Relevance: Review Question	High	High	High

Relevance to Review Focus	Medium	High	Medium
Study Evaluation	Medium	High	Medium

Reference	**CAO, LI and WANG (2014)**	**CHEN, REICHARD and BELIVEAU (2010)**	**CHEUNG, KURUL and OTI (2016)**
code	44C62b40	084 c61b 087	21C43b1
ARTIFACT	Validation of the concept that Isomorphic pressures influences the extent of BIM adoption	Systematic definition of data structure and dependencies of interface information for modeling	Description of the application of a marketing concept (Service-dominant logic) in construction business
Artifact type	Instantiation	Model	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	BIM adoption is a highly socialized activity motivated by rational needs but also driven by isomorphic pressures to be congruent with its specific institutional environment / How Isomorphic pressures impact BIM adoption in construction projects.		Marketing concepts creating value in construction business (service-dominant logic = focus on customer – functionality and form) - To create value by (1) developing new skills and knowledge, (2) customer engagement, (3) supply chain integration, (4) assisting customers to define their value propositions / Creating and enriching dialogues, strengthening networks and guiding customers to self-evaluate products and services
HEURISTIC (Contingencial / Constructive)	Empirically tested with survey data collected from 92 chinese construction projects / Questionnaire surveys and complementary case studies		British: Individually designed National Framework School Programme (NFS) compared with Pre-Designed School Programme (PDS) / Comparison of the focus, benefits and issues among mass production and mass custom-

			ization
Context:	BIM	BIM	BIM / Mass customization
Benefit	LIFECYCLE INTEGRATION: This paper explains how three different types of isomorphic (coercive, mimetic and normative) pressures influence BIM adoption throughout a building lifecycle.	INTEROPERABILITY: The study develops the Interface Object Model which defines the basic data structure and dependecies of interface information to enhance interface modeling	CUSTOMIZATION:The study apply a marketing concept(service-dominant logic) in creating value in the construction business to achieve Mass Customization
STAKEHOLDER:	Architect / Engineer	Contractors	Owner / Facility Manager / Contractors
TOOLS: SOFTWARE / HARDWARE	SmartPLS 2.0 M3 was employed as analysis program	Unified Modeling Language – UML	
Application:		Construction components	
Research center	Tongji University, China; Hong Kong Polytechnic University, China	Ohio State University, USA; Virginia Polytechnic Institute and State University, USA	Birmingham City University, UK; Oxford Brookes University, UK
Research methods	Survey	Case study	Case study
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	High	Medium
Study Evaluation	Medium	High	Medium

Reference	**CHI et al. (2015)**	**LEON et al (2013)**	**DURO-ROYO, MOGAS-SOLDEVILA and OXMAN (2015)**
code	069 C21b 06	23C48b6	18C28b2(95)
ARTIFACT	A representation approach to increase productivity in liquefied natural gas plant	Method for manufacture hyperbolic geometries and their complex intersection patterns through	METHOD: Integrated design and digital fabrication of multimaterial and complex spa-

	construction	CAD/CAM	tial objects; INSTANTIATION: Direct additive manufacturing combining a robotic arm and a multi-syringe multi nozzle material deposition system
Artifact type	Model	Method	Method and Instantiation
What RESULTS do they provoke? / For what kind of PROBLEM?	A Hybrid operation guidance approach can increase productivity in LNG construction plants	Higher level of mass customization: Integration of Design and fabrication information. The restructuring of architecture enables the institutionalization of the seamless collaborative enterprise that was once the role of the “master builder” / Excludes the need for the mediation produced by drawings - Integrated practice methodology and highly collaborative process – Rhino/Grasshopper -	Design and digital fabrication of spatial and material complex objects. A continuous and seamless multi-dimensional design-to-fabrication data flow / integrate design and digital fabrication
HEURISTIC (Contingencial / Constructive)		Limits: Clash detection; context: The “ways-of-making” used by automotive and aerospace industry can be adopted by AEC / “With the integration of CAD with CAM we can achieve higher levels of systematized customization (mass-customization)	Combines a robotic arm and a multi-syringe multi nozzle for water-based material deposition system. / direct additive manufacturing of multi-material objects . By fine-tuning mechanical property gradients and layered compositions of multi-material extrusions, it can be achieved hierachical deposition and material distribution

Context:	BIM	BIM / Mass customization	Digital fabrication / Design to Fabrication
Benefit	PRODUCTIVITY: The study states that tme wasted by getting the right information can lead to cost blowouts. Automation and robotics can help improve productivity / LIFECYCLE INTEGRATIONS: The study states that cloud computing technologies in construction helps deploy suitable versions of construction data at every stage of construction life cycle for different personnel with different purpose.	INTEROPERABILITY: The paper illustrates the collaborative and flexible potential of text-based neutral-life interoperability from multiple sources and an open file structure	CUSTOMIZATION: The study presents a customized and integrated virtual-to-physical computational workflow for design and digital fabrication of objects additively manufactured using a wide-range of materials
STAKEHOLDER:	Architect / Engineer	Contractors	Architect / Engineer / Contractors
TOOLS: SOFTWARE / HARDWARE	AVEVA / HARDWARE: High-definition surveying scanner	MODELING: Rhinoceros / Grasshopper; Digital Project based on Catia	MODELING: Rhinoceros / Grasshopper; C-sharp code written to transmit XML instructions; Qt project; C code using IDE envirinment / 6-axis robotic arm and a deposition platform: Kuka KR AGILUS model KR 10 R1 1000 SIXX WP
Application:	Construction components	Architectural elements	Architectural elements

Research center	Curtin University, Perth, Australia	RMIT University, Australia	Massachusetts Institute of Technology, USA
Research methods	Case study	Experimental	Experimental
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	Medium	Medium
Study Evaluation	Medium	Medium	Medium

Reference	**EASTMAN et al. (2010)**	**FARR, PIROOZFAR and ROBINSON (2014)**	**FETTERMANN (2013)**
code	45C62b51(171)	14C23b1(68)	56C93b1
ARTIFACT	Method to capture detailed level information requirements from end users at the IDM phase of specification, so that all later stages may refer to the specifications for guidance	Testing the development of mass customizable facades using an industry standard BIM application	METHOD: Metodo para identificar e selecionar ferramentas e tecnicas associadas ao desenvolvimento de um produto orientado a customizacao em massa; INSTANTIATION: Validacao de um metodo de desenvolvimento de produto orientado a customizacao em massa, por meio de um projeto de moveis modulados para uma grande loja de vestuario
Artifact type	Method	Instantiation	Method and Instantiation
What RESULTS do they provoke? / For what kind of PROBLEM?	Procedures for developing Information Delivery Manuals(IDM) for Architectural Precast Projects / Anticipate issues of MVD (Model View Definitions) specifications early in the IDM	Investigation of generic capabilities of BIM applications to offer mass customization (Personalised solutions at a price comparable to mass produced products).	Repositorio de conhecimento para gestao do Processo de Desenvolvimento de Produto Niveis de customizacao em massa / Promover a

	(Basic concepts knowledge for achieving full interoperability between BIM tools)	The concepts of 'Super-System','System' and 'sub-system' are presented / Addressing personalised solutions as nearly affordable as possible to what is offered by mass production. The challenge of achieving the benefits of the economies of scale for personalised end products	Customizacao em Massa por meio do Processo de Desenvolvimento de Produto. pagina 126; Pagina 148
HEURISTIC (Contingencial / Constructive)	Research limit: Architectural precast concrete; Research context: IDMs are defined by Industry Domain experts(archtects, engineers); MVDs are defined by IT experts. / IDM documentation: Tables define each "use case" within the processes; other tables define the information exchanges required for the "use cases".	future research need to address sub-system levels of automation and links to HTML and web database application / Customisable façade systems. BIM applications utilized to offer customisable facade systems. BIM applications utilized to offer customisable facade systems	(1) Qualitativo: entrevistas – moveis modulados; (2) Quantitativo: questionarios (3) Revisao bibliografica (4) Desenvolvimento de protocolo (5)Desenvolvimento de ferramenta / Pesquisa exploratoria – Tese estruturada em cinco artigos – Um dos artigos estuda uma Fabrica de moveis e conclui que um tempo reduzido de set up das maquinas CNC permite a Customizacao em Massa sem perda de produtividade
Context:	BIM	BIM / Mass customization	Mass customization
Benefit	INTEROPERABILITY; IFC specifications have several phases such as IDM (that are defined by end users) and MVD (that are	CUSTOMIZATION: A mass customizable facade was developed and partialy tested through the devel-	CUSTOMIZATION; O Estudo desenvolve um mecanismo para identificar e selecionar

	mapped by IT experts). This paper developed methods to capture information at the IDM phase to be refered to at all later stages.	opment of a product family using an industry standard BIM application	metodos, ferramentas e tecnicas associadas ao Processo de Desenvolvimento de Produto orientado a Customizacao em massa / LIFECYCLE INTEGRATION: O estudo mostra que Customizacao em Massa requer produtos com curto ciclo de vida
STAKEHOLDER:	Architect / Engineer / Contractors	Owner / Facility Manager / Contractors	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE		----	MODELING: Promob Studio – moveis modulados; ANALYSIS: Microsoft Excel
Application:	Construction components	Architectural elements	Interior design
Research center	Georgia institute, USA – Israel Institute of Technology, Israel	Newschool of Architecture and Design, USA; University of Brighton, UK	Universidade Federal do Rio Grande do Sul, Brasil
Research methods	Experimental *	Experimental; Case study	Survey *
Relevance: Review Question	High	High	Medium
Relevance to Review Focus	High	High	Medium
Study Evaluation	High	High	Medium

Reference	**FRUTOS (2006)**	**GATTAS and YOU (2016)**	**GIRMSCHEID and RINAS (2012)**
code	57C93b2	17C28b1(91)	46C63b2 (142)
ARTIFACT	de elementos de pio a decisao em izacao em massa. colaborativo que	METHOD: Design-to-fabrication process for folded sandwich structures. INSTANTITATION;	CONSTRUCT: The concept of “Cooperative world”; MODEL:

	…to de passos para …a configuracao de …oduto …STANTIATION: …es de testes e …um sistema de …e um produto …izavel	Design and digital fabrication of an origami-like structural form	A model describing that a cooperative approach leads the construction to a higher level of prefabrication and Mass Customization
Artifact type	Model, Method and Instantiation	Method and Instantiation	Construct and Model
What RESULTS do they provoke? / For what kind of PROBLEM?	Representacao de customizacao em massa considerando-se as visoes de projetistas e clientes / Facilitar a colaboratividade entre projetistas de clientes. - A diminuicao do ciclo de vida dos produtos e a expansao da concorrencia resultaram na falencia de muitas empresas de producao em massa. Pag.62 . Pag. 53 Pag.99	The folded sandwich structures design-to-fabrication process presented, provides advantages over the alternative surface-element such as surface to pattern conversion, manufacture rationalisation and integral connection superposition / Digital fabrication of developable 3D surfaces. Elimination of many fastener components and thus increase the feasibility of digital construciton methods.	Implement mass customization. Understanding the behavior of a complex system of cooperating players / Fragmented processes as a constraint to industrializing the construction industry.
HEURISTIC (Contingencial / Constructive)	Validacao limitado do modelo (estudo de caso hipotetico); Customizacao feita no contexto de um unico produto / Programacao Orientada a Objetos, Analise de decisao multiatributos e programacao linear de inteiros. - Trade-of entre produtividade e variedade	Limitations: non-uniform building structures. Origami-like structural forms in which building component parameters are inherently dependant upon building surface parameters / : (1)Minimum number of unique elements; (2) Element definitions constrained by surface and manufacturing; (3) Flexible generation of CNC-manufacturable parts.	In Switzerland the construction industry is still characterized by manual production techniques and small-scaled companies / Theory-led structuration of a business model.

Context:	Mass customization	Digital fabrication / Design to Fabrication	Mass customization
Benefit	CUSTOMIZATION; Um modelo para representacao de configuracao em massa considerando-se as visoes de projetistas e clientes; Producao em massa e customizacao em massa nao devem ser visualizados como proposicoes excludentes	CUSTOMIZATION: The paper presents a design-to-fabrication process for folded sandwich (origami-inspired) structures where building component parameters are dependant upon building surface parameters.	CUSTOMIZATION: The paper defines the concept that a Cooperative Business Model enables to implement mass customization in the prefabrication industry; LIFECYCLE INTEGRATION: The paper develops a model stating that a cooperative business approach optimized building lifecycles
STAKEHOLDER:	Owner / Facility Manager / Architect / Engineer	Architect / Engineer / Contractors	Architect / Engineer / Contractors / Subcontractor / Fabricator
TOOLS: SOFTWARE / HARDWARE	ANALYSIS: JAVA Visual Basic; Microsoft Excel; REPOSITORY: ACCESS	MODELING: MATLAB / FABRICATION: 2D CNC router	
Application:		Architectural elements	
Research center	Universidade Federal do Rio Grande do Sul, Brasil	University of Queensland, Australia; University of Oxford, UK	ETH Zurich, Switzerland
Research methods	Experimental	Experimental *	Survey *
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	High	Medium
Study Evaluation	Medium	High	Medium

Reference	**GOULDING, RAHIMIAN and WANG (2014)**	**HENRIQUES (2013)**	**HOU et al. (2015)**

code	06c21b12	59C93b4	081 c61b 60
ARTIFACT	Description of a web based environment for a construction site simulation	Metodo de otimizacao e melhoria continua do processo de projeto de construcoes metalicas com base nos conceitos de customizacao em massa	Evaluation of the feasibility of Augmented Reality to improve piping assembly productivity
Artifact type	Model	Method	Instantiation
What RESULTS do they provoke? / For what kind of PROBLEM?	Cloud-based BIM in Virtual Reality as an aid within the complexity of communication within AEC. / Sharing information for geographically dispersed end users	Referencial para um sistema estrutural modulado e que possibilite customizacao para diferentes tipologias e terrenos / Sistemas construtivos em aco no Brasil tem caracteristicas artesanais tanto no que se refere aos materiais quanto aos processos de projeto e producao	Empirical boost for the use of Augmented Reality in construction piping assembly
HEURISTIC (Contingencial / Constructive)	Collaborative design teams,. Web-based game-like Virtual Reality Construction site Simulator / Web-based virtual reality cloud platform, Web-based project collaboration	, rificacao da eficiencia do modelo proposto; desenvolvimento de propotipos de conexoes e ligacoes e simulacao / Utilizacao de projetos padronizados contendo diferentes formas de conexao, possibilitando diferentes configuracoes de customizacao (Pag.,140,147,164)	
Context:	BIM	Mass customization	BIM

Benefit	INTEROPERABILITY:The study develops a Web-based model beneficial for sharing relevant information / LIFECYCLE INTEGRATION:The paper presents a cloud-based Virtual Reality construction site simulator to analysing issues such as design, process, logistic and supply chain concerns.	PRODUCTIVITY: o Estudo conclui que a otimizacao do processo de projeto aumenta a produtividade; CUSTOMIZATION: O estudo desenvolve um sistema estrutural modulado para edificacoes customizadas em aco	PRODUCTIVITY The study shows the feasibility of Augmented Reality to improve the assembly productivity by lowering cognitive workload
STAKEHOLDER:	Architect / Engineer	Contractors / Architect / Engineer	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	MODELING: Quest3DTM, EONReality, TM and Virtools, Autocad, 3DstudioMax ANALYSIS: MSProject, HTML, , ASP.net REPOSITORY: Rhino		Statistical Analysis Software – SAS
Application:		Construction components	Construction components
Research center	University of Central Lancashire, UK – Curtin Unuversity, Australia	Universidade Federal de Ouro Preto, Brasil	Curtin University, Perth, Australia; Woodside Energy Ltd, Australia
Research methods	Action-Research *	Survey *	Experimental
Relevance: Review Question	High	Medium	Medium
Relevance to Review Focus	High	Medium	Medium
Study Evaluation	High	Medium	Medium

Reference	**JEONG et al. (2009)**	**KARAMAN and RATNAGARAN (2013)**	**KHALILI and CHUA (2013)**
code	10C21b25	074 C21b 20	35C61b61

ARTIFACT	Tests to guide the use of IFC for data exchange between BIM tools on precast concrete	on of the concept handling exact etry data is vital ause tolerance nulated through ous stages of ing life cycle is error-prone	An IFC based model aiming to minimize the number of precast prefabricated structural elements
Artifact type	Instantiation	Instantiation	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	Data exchange between BIM tools with the focus on the domain of precast concrete facades. Typical exchange scenario between architect and precast fabricator. / To explore the current state-of-the-art of data Interoperability	3-D parametric description of highway geometry suitable for the data-exchange integrity required throughout the life cycle of a steel bridge	Determine a configuration of components that minimize the total prefabrication cost / To extract topological relationships and geometrical properties from the IFC file
HEURISTIC (Contingencial / Constructive)	Imperfect exchanges arose from the lack of uniformity in the way the internal object schemas are mapped to IFC objects and properties / The data interoperability check was a roundtrip export/import test for each tool; Architectural BIM tools and Precast concrete BIM tools		The computation time in this model exponentially increases with the number of building elements in each construction cycle / IFC-based framework
Context:	BIM	BIM	BIM
Benefit	INTEROPERABILITY:The paper performs tests for precast concrete BIM data exchange concluding that despite progress in IFC much work is still needed to achieve fully effective interoperability	LIFECYCLE INTEGRATION: The study validates the concept that handling exact geometry data is vital because tolerance accumulated	INTEROPERABILITY:The paper Develops an IFC-based system to minimize the total number of precast, prefabricated

		through various stages of building life cycle is error-prone	building elements to reduce the production, transportation and installation cost
STAKEHOLDER:	Architect / Engineer; Contractors;Subcontractor / Fabricator	Architect / Engineer	Contractors
TOOLS: SOFTWARE / HARDWARE	MODELING: Revit; Archicad; Digital Project; Bentley Architecture, Tekla Structure; Structureworks precast; SHARING: IFC 2x3	LandXML; finite element software: ANSYS Mechanical APDL; tekla Structures; data exchange formats: XML, Industry Foundation Classes, Integrated Structural Modeling	MODELING: ArchiCAD and C#.net; SHARING: IFC
Application:	Construction components	Construction components	Construction components
Research center	Georgia institute, USA – Israel Institute of Technology, Israel	State University of New York, USA; Istanbul Technical University, Turkey	National University of Singapore, Singapore
Research methods	Experimental	Experimental; Case study	Case study
Relevance: Review Question	Medium	High	High
Relevance to Review Focus	Medium	Medium	High
Study Evaluation	Medium	Medium	High

Reference	**KHANZODE, FISCHER and REED (2008)**	**KIM et al. (2015)**	**LEE et al. (2014)**
code	11c21b28	079 C61b 35	088 c61b 092
ARTIFACT	A set of guidelines for the application of BIM / VDC tools	The concept of "Scaffolding Planning Generator", a	Repreentation of an object-relational IFC server using object-

	for the coordination of technically challenging MEP projects	vocabulary for the selection of scaffoldings	relational database
Artifact type	Instantiation	Construct	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	Benefits and lessons learned / Clash detection and conflicts between subcontractors	Cast-in-place is a highly customized on site work	
HEURISTIC (Contingencial / Constructive)	MEP coordination process using BIM and Virtual Design and Construction (VDC); Class detection, labor saving, less rework / Navisworks and various other softwares		
Context:	BIM	BIM	BIM
Benefit	PRODUCTIVITY: The study captures a series of guidelines for doing MEP coordination using BIM / VDC.	PRODUCTIVITY: The study defines the principles for an appropriate selection of scaffoldings through a semiautomated use of the Scaffolding Selection Process concept	INTEROPERABILITY: Through an object-relational database the study develops an object-relational IFC, aiming to improve query performance by simplifying the mapping process of the inheritance structure and the aggegation concepts
STAKEHOLDER:	Owner / Facility Manager / Subcontractor / Fabricator	Contractors	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	MODELING: Autodesk Architectural Desktop, Revit Structure, QuickPen 3D Pipe Design, CAD Duct, SprinkCAD, ANALYSIS: Navisworks jestream,ETABS Structural analysis	AutoCAD, Visual Basic	IFC 2x3; CUBRID: object-relational database management system; Mapping algorithm: CIS2SQL; C++; C#;
Application:	Construction com-	Construction	Construction compo-

	ponents	components	nents
Research center	Stanford University and DPR construction Inc	DPR Construction, USA; Stanford University, USA	Yonsei University, Korea
Research methods	Experimental; Case study	Case study	Modeling *; Case Study
Relevance: Review Question	Medium	High	High
Relevance to Review Focus	Medium	Medium	High
Study Evaluation	Medium	Medium	High

Reference	**LEE and KIM (2012)**	**LUTH (2011)**	**MACHADO (2005)**
code	20C42b8 (140)	34C61b55	58C93b3
ARTIFACT	METHOD: Stretch and bending method to fabricate mass customized double-curved metal panels; INSTANTIATION: Fabrication of approximately 22,000 double curved panels using the team's developed method of multipoint stretch forming	The concept of "engineering continuum”	Descricao de fatores catalizadores da implementacao de customização em massa.
Artifact type	Method and Instantiation	Construct	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	Sheet metal processing technique to fabricate double-curved metal panels. / double-curved metal panels	A single Building information model that is used throughout the building life-cycle, perform various analysis and modify the data for design, construction and facilities management. / The use of “design intent” rather than models that accurately depict the details of the construction	Identificar fatores desencadeadores e habilitadores da adocao de customizacao em massa e criterios para selecao dos componetes dos produtos a serem customizados /

HEURISTIC (Contingencial / Constructive)	Precision and a limited budget as a key requirement. The idea was developed and elaborated through four mock-up tests over a year and interviews with metal-panel fabricators. / Hybrid sheet metal forming method of multipoint forming and stretch bending	The model should be independent of the individual software package and graphical interface that are used to manipulated data. "The definitions of design and construction engineering are symmetrical and differ only in emphasis and nuance" / Fourth generation computer technologies, BIM and virtual design and construction offer a way to the integrated process for design and construction. Virtual Design and Construction (VDC) are third generation design-construction computing technologies	Customizacao em massa para pequenas e medias empresas Pag.367 Todeschini
Context:	Digital fabrication / Mass customization	BIM	Mass customization
Benefit	CUSTOMIZATION: This study developed an affordable technique (multipoint stretch forming method) to fabricate double-curved unique panels	INTEROPERABILITY:The study states that "If the database follows a universal standard for schema and content, there is no need for interoperability – everyone operates on the same database" / LIFECYCLE INTEGRATION: The study argues that "The engineering on a project is a continuum with elements of both construction and design engineering echoing throughout the entire life cycle"	CUSTOMIZATION; O Estudo desenvolve um framework com o objetivo de identificar principais catalizadores da Customizacao em Massa/ PRODUCTIVITY; O estudo afirma que a introducao de TI (robotica) nos processos industriais traz como beneficio a melhoria da produtividade, e Customizacao em Massa e retrabalho reduzem a produtividade

STAKEHOLDER:	Architect / Engineer / Subcontractor / Fabricator	Owner / Facility Manager / Architect / Engineer / Contractors / Subcontractor / Fabricator	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	MODELING: Digital Project; a custom developed software application for the multipoint stretch forming machine / FABRICATION: 5-axis robot arm; laser cutting bed	MODELING:Tekla Structures	
Application:	Architectural elements	Construction components	Interior design
Research center	Yonsei University, Korea; Gehrt Technology Asia Ltd, China	Luth and Associates Inc, USA	Universidade Federal de Pernambuco, Brasil
Research methods	Experimental; Case study	Case study	Case study
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	High	High
Study Evaluation	Medium	High	High

Reference	MORAIS (2011)	NAWARI (2012)	OSWALD (2014)
code	54C81b3	47C63b3(141)	098 c73b 02
ARTIFACT	Validacao do uso de fabricacao digital em sistemas de customizacao de massa, atraves da fabricacao de um modelo da Catedral de Brasilia	A method that provides digital schema and provisions for efficient BIM application in the prefabrication industry	Validating the feasibility of digital design and fabrication of complex geometry by glulam bows objects
Artifact type	Instantiation	Method	Instantiation

What RESULTS do they provoke? / For what kind of PROBLEM?	Demonstrar que a fabricacao digital e economicamente promissora na industria AEC / Elaboracao de um modelo 3D de uma coluna da catedral de Brasilia	Ability to capture all relevant construction data from BIM models and exchange those data between project stakeholders / What information should be exchanged? How to formulate the information requirements?	Parametric design for curved glulam geometry
HEURISTIC (Contingencial / Constructive)	O arfetato fabricado em maquina CNC seguiu rigosoramente o projeto. O artefato cortado manualmente for executado diferente do projeto. / Fabricacao de dois modelos: (1) Fabricacao tradicional por uma empresa de serralheria, (2) Fabricacao Digital utilizando tecnologia CNC de corte a plasma	Description of building construction processes. Definition of data exchange requirements between construction stakeholders / Process map created using Business Process Modeling Notation (BPMN)	
Context:	Mass customization / Design to Fabrication	BIM	Design to Fabrication
Benefit	CUSTOMIZATION: Este estudo mostra que o uso de CAD/CAM para Fabricacao Digital em sistemas de Customizacao em Massa ainda e pouco comum na arquitetura	PRODUCTIVITY: To help to improve off-site construction productivity, the paper develops a method to provide the digital schema and provisions for efficient BIM application in the prefabrication industry; INTEROPERABIL-	CUSTOMIZATION: The paper studies the parametric design and fabrication of a structural and architectural timber trellis

		ITY; The paper proposes an Information Delivery Manual (IDM) that provides description of BIM standard in off-site construction processes	
STAKEHOLDER:	Architect / Engineer	Architect / Engineer / Contractors	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	MODELING: 3D Studio Max, FormZ; CATIA / FABRICATION: maquina de corte CNC SigmaNEST		SAP 2000; Grasshopper/Rhinoceros / CNC milling machines
Application:	Construction components	Construction components	Architectural elements
Research center	Universidade de Brasilia, Brasil	University of Florida, USA	Guy Nordenson and Associates, USA
Research methods	Experimental *	Survey *	Experimental; Case study
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	High	Medium
Study Evaluation	Medium	High	Medium

Reference	**RAMAJI and MEMARI (2016)**	**REZGUI and MILES (2010)**	**ROCHA (2011, Page 186)**
code	080 c61b 57	50C64b7	61C93b6
ARTIFACT	Relationship among information required for industrial design of typical multistory buildings	The concept of "Small and Medium sized Enterprise alliances"	CONSTRUCT: Refine of a set of concepts related to Mass Customization; MODEL: Representation of customisation strategies in the house-building sector; METHOD: Proposal of a se-

			quence of ateps for defining a customization strategy; INSTANTIATION: Implementing a method for defining customization strategy aiming to assess its utility
Artifact type	Model	Construct	Construct, Model, Method, Instantiation
What RESULTS do they provoke? / For what kind of PROBLEM?	The Product Architecture Model is developed to better serve products that are highly customizable	Allow SME to compete in new ways, get better reward for their work and gain financial strenght. Small and Medium Enterprises (SME) alliance modes of operations promotes process innovation / Partnering in SME construction sector.	The framework entails ten decision categories that define the scope of a customization strategy and also address some aspects of the client's interfaces, products design and operations areas / Defining Customization strategies - "...short and unpredictable life cycles create a turbulent market, which is a favourable environment for customized products."
HEURISTIC (Contingencial / Constructive)		SME alliances are built around a set of clearly defined but customizable roles / A long-term SME alliance permits better process integration with tools and methods that ease interoperability	Design Science Research – The primary contribution of this investigation is the constructs and the relatioship established among them (model) / "A high rate of technological changes reduces the life cycle of products, favouring the development of customisation strategies"

Context:	BIM	Mass customization	Mass customization
Benefit	LIFECYCLE INTEGRATION: The study develops the Product Architecture Model that enhances productivity and interoperability and may be used throughout the building lifecycle	LIFECYCLE INTEGRATION: a group of partners interacting throughout a project lifecycle adds value across the supply chain	CUSTOMIZATION: The study develops a sequence of steps for defining a customization strategy, depicted in ten decision categories
STAKEHOLDER:	Architect / Engineer	Contractors / Subcontractor / Fabricator	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	A conventional object-oriented graphical language called Unified Modeling Language (UML)		
Application:			Construction components
Research center	Pennsylvania State University, USA;	Cardiff University, UK	Universidade Federal do Rio Grande do Sul, Brasil
Research methods	Modeling *	Case study	Design Science Research
Relevance: Review Question	High	High	High
Relevance to Review Focus	Medium	Medium	High
Study Evaluation	Medium	Medium	High

Reference	**SACKS et al. (2010)**	**SAID (2015)**	**SCHNEIDER (2014)**
code	09C21b23	48C63b5(145)	63C93b8
ARTIFACT	Experiment aiming to test the viability of using BIM for design and	Description of a set of mutually rewarding rela-	. two-stage model e product families; ATION: Verify the

	fabrication of architectural precast facades	tions among electrical contractors	wo-stage model to product families modelling of an transfer switch
Artifact type	Instantiation	Model	Model and Instantiation
What RESULTS do they provoke? / For what kind of PROBLEM?	Data exchange in design and fabrication of precast facades / Interoperability: the IFC classes schema lacks precast-specific entities and property sets	promoting mutually-rewarding relations among stakeholders. / start or improve prefabrication in construction	To have an efficient customization process without compromizing the product family / The difficult and challenging task of designing a Product Family - Three key elements for mass customization: (1) A system to draw customers requirements interactively(2)A flexible manufacturing system that can reduce the trade-of between variety and productivity,(3)A logistic system capable of delivering the right prodcut to the right client
HEURISTIC (Contingencial / Constructive)	Generating from BIM the same set of drawings generated from CAD process showed a productivity gain of 57%. However, the exchange of data between BIM tools were inconsistent and incomplete / The Rosewood experiment: Design and fabrication using traditional CAD and while independently using BIM tools	increasing implementation of lean principles. A set of data-driven best practices and improvement opportunities for electrical contractors to promote mutually-rewarding relations among stakeholders / Identifying prefabrication best practices and	It is necessary to allow the customers participate more deeply into the design stage of mass customization process, but if too much flexibility is provided to the customer , the customization process may get in trouble at the design or manufacuring process

		suggesting opportunities for improvement in the electrical construction sector	/ Defining conditions for which the customization process becomes backtrack-free (the customer specifies the product he needs without going into dead ends)
Context:	BIM	BIM	Mass customization
Benefit	INTEROPERABILITY:The experiment demonstrated the viability of using BIM for design and fabrication of precast facades; however, data exchange between architectural and engineering systems were incomplete and inconsistent	PRODUCTIVITY: The study finds that manufacturers can collaborate to improve onsite productivity by developing products that can flexibly accommodate different sittuations; CUSTOMIZATION: The study presents the findings that principles of Mass customization can be applied in prefabrication operations to use standardized modules that facilitate an acceptable number of design variants.	CUSTOMIZATION: The study develops a two-stage model to customize product families. First, a solution consistent with the client's requirements. Second, this solution is used to transform a generic product into a member of a product family.
STAKEHOLDER:	Architect / Engineer; Contractors	Contractors / Subcontractor / Fabricator	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	MODELING: Revit, Tekla Structures; SHARING: IFC version 2x3		
Application:	Architectural elements		
Research center	Georgia institute, USA – Israel Institute of Technology, Israel	Santa Clara University, USA	Universidade Estadual de Campinas, Brasil

Research methods	Experimental	Survey *	Modeling *
Relevance: Review Question	Medium	High	High
Relevance to Review Focus	Medium	Medium	High
Study Evaluation	Medium	Medium	High

Reference	**SOLNOSKY and LUTH (2015)**	**STAVRIĆ and WILTSCHE (2012)**	**TAYLOR and BERNSTEIN (2016)**
code	33C61b52	16C27b2	32C61b47
ARTIFACT	An Integrated Structural Process Model to promote advances in the design through collaboration and integration among participants	A sequence of steps from design to fabrication of 3D ornamental parts by a robotic arm using 3D NURBS	A model that describes an evolutionary trajectory a firm evolves as it gains experience using BIM tools and as it shares electronic BIM files
Artifact type	Model	Method	Model
What RESULTS do they provoke? / For what kind of PROBLEM?	A wide comprehensive range of processes, tools and information / The AEC industry is highly fragmented among different disciplines throughout the lifecicle of a building	1) Congruent partes of a cube generaterd by planes and cylindrical sections; 2)Spatializing a 2d ornament by two approaches: Mapping and blocks / The complexity of the subject of ornamentation	BIM practice evolve cumulative along a trajectory of four paradigms: visualization, coordination, analysis and supply chain integration / To understand and develop interorganizational work practices to reap the benefits of BIM
HEURISTIC (Contingencial / Constructive)	Limitation: ISPM was not directly implemented into practice but was verified against current practices across several projects / An Integrated Structural Process Model (ISPM) to promote advances in the design of structural systems through col-	Apply the modularity of ornaments avoiding repetition of basic geometric shapes / The use of digital tools to generate 3D models	Addressing technological interoperability is not sufficient to unleash the benefits of integrated technologies / (1)Visualization (2)Coordination (3)Analysis (4)Supply chain integration

	laboration and integration among participants		
Context:	BIM	Digital fabrication / Design to Fabrication	BIM
Benefit	INTEROPERABILITY: The study provides guidance in the software development examining the interoperability of transferring information (metadata from software to software) / LIFECYCLE INTEGRATION: The study Developed and integrated a life-cycle process that uses the basis of Unbounded Integrated Practices and BIM that can be expanded upon as new technologies emerge	LIFECYCLE INTEGRATION: A method for digital flow from design to fabrication using 3D NURBS modeling software for code generation and a robotic arm to fabricate.	PRODUCTIVITY: The paper builds a model based on the premise that firms that share their BIM files achieve improvements in productivity and efficiency. INTEROPERABILITY:The paper builds a model based on the premise that interoperability of business practices must complement technological interoperability.
STAKEHOLDER:	Architect / Engineer / Contractors	Architect / Engineer / Contractors	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE		MODELING: Rhinoceros / Grasshopper / FABRICATION: industrial robot arm IRB 140 produced by ABB	
Application:	Construction components	Architectural elements	
Research center	University Park, USA; Luth and Associates Inc, USA	Graz University of Technology, Austria	Columbia University, USA; Yale University, USA
Research methods	Grounded Theory	Experimental	Survey
Relevance: Review Question	High	Medium	Medium

Relevance to Review Focus	Medium	Medium	Medium
Study Evaluation	Medium	Medium	Medium

Reference	**VENUGOPAL (2011)**	**WANG and LEITE (2016)**	**WU and ISSA (2015)**
code	097 c72b 03	43C62b34(129)	077 c61b 09
ARTIFACT	MODEL: Developing modular and reusable Model View Definitions from IFC Product Model sub-schemas; INSTANTIATION: validating a new approach to define Model View Definitions through a precast concrete component	METHOD: A method for capturing and representing process information such as discussions and decisions in the design process INSTANTIATION; A Use Case Diagram of capturing process information in Mechanical, Electrical and pumbling design.	BIM Execution Process Model to integrate building lifecycle and improve LEED project outcomes.
Artifact type	Model and Instantiation	Method and Instantiation	Method
What RESULTS do they provoke? / For what kind of PROBLEM?	Developing modular and reusable MVDs from IFC Product Modeling Concepts	3D representations of clashes and solutions. / Little is discussed regarding capturing and representing process information in a computer-interpretable manner.	Integrated Building Lifecycle Process Map is based on the third level of Integrated Building Process Model to enable efficient design at the building system level
HEURISTIC (Contingencial / Constructive)		information generated during design coordination process can be used in further model-based analysis. / linkage between review markups	

		and model componets. A prototype system was developed to capture process information	
Context:	BIM	BIM	BIM
Benefit	INTEROPERABILITY: The paper develops and tests a method to build reusable MVDs based on formal definitions of IFC Product Modeling Concepts	LIFECYCLE INTEGRATION: In current practices process information is rarely documented formally. This paper creates a system to capture and formalize design process and other building life cycle information.	INTEROPERABILITY: The study develops an integrated Green BIM Process Map based upon Process Execution Planning Guidelines: What information needs to be exchanged? What format? What business rules? When and between whom?
STAKEHOLDER:	Architect / Engineer	Contractors / Subcontractor / Fabricator	Architect / Engineer
TOOLS: SOFTWARE / HARDWARE	EXPRESS: base language for IFC	ANALYSIS: Autodesk Naviswork Manage; Visual Studio C#; Dot NET 3.5 Framework; Unified Modeling Language (UML) / PROCESSING: PC with 1.60-2.7 GHz processor and 4-8 GB RAM; High resolution touch screen system	Business process model and notation (BPMN); Microsoft Visio
Application:	Construction components	Construction components	
Research center	Georgia institute, USA – Israel Institute of Technology, Israel	University of Texas, USA	California State University, USA; University of Florida, USA
Research methods	Modeling *; Case study	Survey *	Modeling *; Case Study
Relevance: Review Question	High	High	Medium
Relevance to Review Focus	High	Medium	Medium

Study Evaluation	High	Medium	Medium

Appendix B - Forms for Conducting the Systematic Review: Emerald

Form code: C01b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date: 2016/Nov14

Keywords: BIM / Fabrication

Strings:

BIM AND Fabrication - [Abstract: bim] AND [Abstract: fabrication] AND [Publication Da... (Articles/Chapters - 0)

BIM AND Fabrication - [Publication Title: bim] AND [Publication Title: fabrication] A... (Articles/Chapters - 0)

BIM AND Fabrication - [Keywords: bim] AND [Keywords: fabrication] AND [Publication Da... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles

Form code: C02b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date: 2016/Nov14

Keywords: “Building Information Modeling” / Fabrication

Strings:

“Building Information Modeling” AND Fabrication - [Abstract: "building information modeling"] AND [Abstract: fabr... (Articles/Chapters - 0)

“Building Information Modeling” AND Fabrication - [Publication Title: "building information modeling"] AND [Publi... (Articles/Chapters - 0)

“Building Information Modeling” AND Fabrication - [Keywords: "building information modeling"] AND [Keywords: fabr... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include:

All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles

Form code: C03b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date: 2016/Nov14

Keywords: BIM / Mass Customization

Strings:

BIM AND Mass Customization - [Abstract: bim] AND [Abstract: mass customization] AND [Publica... (Articles/Chapters - 0)

BIM AND Mass Customization - [Publication Title: bim] AND [Publication Title: "mass customiz... (Articles/Chapters - 0)

BIM AND Mass Customization - [Keywords: bim] AND [Keywords: "mass customization"] AND [Publi... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles.

Form code: C04b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date: 2016/Nov14

Keywords:“Building Information Modeling”/Mass Customization

Strings:

“Building Information Modeling” AND Mass Customization - [Abstract: "building information modeling"] AND [Abstract: mass... (Articles/Chapters - 0)

“Building Information Modeling” AND Mass Customization - [Publication Title: "building information modeling"] AND [Publi... (Articles/Chapters - 0)

“Building Information Modeling” AND Mass Customization - [Keywords: "building information modeling"] AND [Keywords: mass... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles.

Form code: C05b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date:2016/Nov14

Keywords:BIM/Digital Fabrication

Strings:

BIM AND Digital Fabrication - [Abstract: bim] AND [Abstract: digital fabrication] AND [Public... (Articles/Chapters - 0)

BIM AND Digital Fabrication -[Publication Title: bim] AND [Publication Title: digital fabric... (Articles/Chapters - 0)

BIM AND Digital Fabrication -[Keywords: bim] AND [Keywords: digital fabrication] AND [Public... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles

Form code: C06b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date:2016/Nov14

Keywords:"Building Information Modeling"/Digital Fabrication

Strings:

"Building Information Modeling" AND Digital Fabrication - ["building information modeling"] AND [Abstract: digi... (Articles/Chapters - 0)](#)

"Building Information Modeling" AND Digital Fabrication -[Publication Title: "building information modeling"] AND [Publi... (Articles/Chapters - 0)

"Building Information Modeling" AND Digital Fabrication -[Keywords: "building information modeling"] AND [Keywords: digi... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Studies list: This search did not match any articles.

Form code: C07b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

http://www.sbu.unicamp.br/

Search date:2016/Nov/14

Keywords:Design to Fabrication/Architecture

Strings:

Design to Fabrication AND Architecture - [Abstract: design to fabrication] AND [Abstract: architecture]... (Articles/Chapters - 23)

Design to Fabrication AND Architecture – [Publication Title: design to fabrication] AND [Publication Tit... (Articles/Chapters - 0)

Design to Fabrication AND Architecture -[Keywords: design to fabrication] AND [Keywords: architecture] ... (Articles/Chapters - 0)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: From January 1997 to November 2016

Search history (Abstract):

Rapid Prototypes (5);Porous Materials (4);Scaffolds (4);Biological Analysis And Testing (3);+More

Last Year (2)

Rapid Prototyping Journal (13);Industrial Robot (3);Circuit World (1);COMPEL (1);+More

Engineering (17);Mechanical engineering (16);Electrical & electronic engineering (4);Building & construction (1);+More

Research paper (11);Technical paper (3);Case study (1);General review (1)

Search history (Abstract):

Studies list:

1 Xiang Li, Dichen Li, Bingheng Lu, Yiping Tang, Lin Wang, Zhen Wang,,Design CAP scaffolds by indirect solid free form fabrication,Type:

Case study,Volume: 11 Issue: 5,Rapid Prototyping Journal,2005

2 Richard Bloss,Robots have come to architecture to model, construct, fabricate and offer new approaches to create innovative designs,

elements and structures,,Volume: 41 Issue: 5,Industrial Robot: An International Journal,2014

3 Annalisa Tirella, Carmelo De Maria, Giuseppe Criscenti, Giovanni Vozzi, Arti Ahluwalia,The PAM2 system: a multilevel approach for fabrication of complex three-dimensional microstructures,Volume: 18 Issue: 4,Rapid Prototyping Journal,2012

4 Ker Chin Ang, Kah Fai Leong, Chee Kai Chua, Margam Chandrasekaran,Investigation of the mechanical properties and porosity relationships in fused deposition modelling-fabricated porous structures,Volume: 12 Issue: 2,Rapid Prototyping Journal,2006

5 Xiang Li, Chengtao Wang, Wenguang Zhang, Yuanchao Li,Fabrication and compressive properties of Ti6Al4V implant with honeycomb-like structure for biomedical applications,Volume: 16 Issue: 1,Rapid Prototyping Journal,2010

6 A. Bandyopadhyay, R.K. Panda, T.F. McNulty, F. Mohammadi, S.C. Danforth, A. Safari,Piezoelectric ceramics and composites via rapid prototyping techniques,Volume: 4 Issue: 1,Rapid Prototyping Journal,1998

7 Yujie Quan , Philipp Drescher , Faming Zhang , Eberhard Burkel , Hermann Seitz,Cellular Ti6Al4V with carbon nanotube-like structures fabricated by selective electron beam melting,Volume: 20 Issue: 6,Rapid Prototyping Journal,2014

8 Joseph Fjelstad, Kevin Grundy, Gary Yasumura,3D PCB architecture for next generation high speed interconnections,Volume: 31 Issue: 4, Circuit World,,2005

9 Ramakrishna Vasireddi , Bikramjit Basu,Conceptual design of three-dimensional scaffolds of powder-based materials for bone tissue engineering applications,Volume: 21 Issue: 6,Rapid Prototyping Journal,2015

10 T. Patrício , M. Domingos , A. Gloria , U. D'Amora , J.F. Coelho , P.J. Bártolo,Fabrication and characterisation of PCL and PCL/PLA scaffolds for tissue engineering,Volume: 20 Issue: 2,Rapid Prototyping Journal,2014

11 F. Wang, L. Shor, A. Darling, S. Khalil, W. Sun, S. Güçeri, A. Lau,Precision extruding deposition and characterization of cellular poly-ε-caprolactone tissue scaffolds,Volume: 10 Issue: 1,Rapid Prototyping Journal,2004

12 Nima Enayati, Farid Najafi,Design and manufacturing of a tele-operative rescue robot with a novel track arrangement,Volume: 38 Issue: 5,

Industrial Robot: An International Journal,2011

13 J. Giannatsis, V. Dedoussis, D. Karalekas,Architectural scale modelling using stereolithography,Volume: 8 Issue: 3,Rapid Prototyping Journal,2002

14 Krishna C R Kolan , Albin Thomas , Ming C Leu , Greg Hilmas,In vitro assessment of laser sintered bioactive glass scaffolds with different pore geometries,

Volume: 21 Issue: 2,Rapid Prototyping Journal,2015

15 Mei-Ling Yeh, Yao-Chian Lin, Wei-Chieh Chang,An 11 GHz low-phase-noise voltage-controlled oscillator,Volume: 29 Issue: 2,Microelectronics International: An International Journal,2012

16 Miguel Abambres , Wai-Meng Quach,Residual stresses in steel members: a review of available analytical expressions, ,International Journal of Structural Integrity,2016

17 Fikri Serdar Gokhan, Gunes Yilmaz,Solution of Raman fiber amplifier equations using MATLAB BVP solvers,Volume: 7 Issue: 1,COMPEL –

The international journal for computation and mathematics in electrical and electronic engineering,2011

18 Ana Pilipović , Bogdan Valentan , Mladen Šercer,Influence of SLS processing parameters according to the new mathematical model on

flexural properties,

Volume: 22 Issue: 2,Rapid Prototyping Journal,2016

19 Kejun Ning,Research on embedded MAS based manipulator control,Volume: 33 Issue: 2,Industrial Robot: An International Journal,,2006

20 ,Recognizing successful innovation: Awarding the UK's premier prize for engineering innovation,Volume: 25 Issue: 10,Strategic Direction,2009

21 Wenxi Chen, Daming Wei, Shuxue Ding, Michael Cohen, Hui Wang, Shigeru Tokinoya,Naotoshi Takeda,A scalable mobile phone-based system for multiple

vital signs monitoring and healthcare,Volume: 1 Issue: 2,International Journal of Pervasive Computing and Communications,2005

22 C. De Maria , L. Grassi , F. Vozzi , A. Ahluwalia , G. Vozzi,Development of a novel micro-ablation system to realise micrometric and well-defined hydrogel

structures for tissue engineering applications,Volume: 20 Issue: 6,Rapid Prototyping Journal,2014

23 Long D. Nguyen , Hung T. Nguyen,Relationship between building floor and construction labor productivity: A case of structural work,

Volume: 20 Issue: 6,Engineering, Construction and Architectural Management,2013

Study	Exclusions criteria	Status
1	8	Excluded
2	4	Excluded
3	8	Excluded
4	7	Excluded
5	7	Excluded
6	8	Excluded
7	7	Excluded

8	4	Excluded
9	4	Excluded
10	7	Excluded
11	7	Excluded
12	8	Excluded
13	8	Excluded
14	8	Excluded
15	8	Excluded
16	4	Excluded
17	4	Excluded
18	4	Excluded
19	4	Excluded
20	4	Excluded
21	8	Excluded
22	8	Excluded
23	8	Excluded

Form code: C08b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date:2016/Nov/14

Keywords:Design to fabrication/Manufactur*

Strings:

"Design to fabrication" AND Manufactur* [Abstract: "design to fabrication"] AND [Abstract: manufactur*]... (Articles/Chapters - 1)

"Design to fabrication" AND Manufactur* [Publication Title: "design to fabrication"] AND [Publication T... (Articles/Chapters - 0)

Design to fabrication AND Manufactur* [Keywords: design to fabrication] AND [Keywords: manufactur*] A... (Articles/Chapters - 3)

(Abstract, Publication title, Keywords)

Filters Applied:

Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: All dates

Search history(*Abstract)*:

Last Year (1) Last 6 Months (1) Last 3 Months (1

Search history(*Keywords)*:

Design (2) Fabrication (2) Advanced Manufacturing Technologies (1) Assembly (1)

Last Year (1)

Last 6 Months (1)

Studies list:

1 - Fritz Stöckli , Fabio Modica , Kristina Shea,Designing passive dynamic walking robots for additive manufacture,Volume: 22 Issue: 5,Rapid Prototyping Journal,2016
2 - Haeseong Jee, Emanuel Sachs,Surface macro-texture design for rapid prototyping,Volume: 6 Issue: 1,Rapid Prototyping Journal,2000
3 - Romy Francis , Joseph Newkirk , Frank Liou,Investigation of forged-like microstructure produced by a hybrid manufacturing process,Volume: 22 Issue: 4,Rapid Prototyping Journal,2016
4 - Xubin Su, Yongqiang Yang, Di Wang, Yonghua Chen,Digital assembly and direct fabrication of mechanism based on selective laser melting,Volume: 19 Issue: 3,Rapid Prototyping Journal,201

Study	Exclusions criteria	Status
1	8	Excluded
2	8	Excluded
3	8	Excluded
4	8	Excluded

Form code: C09b

Source: Emerald Insight – Advanced Search

http://www-emeraldinsight-com.ez88.periodicos.capes.gov.br/search/advanced

Search date: 2016/Nov/14

Keywords: Design to fabrication/ Construction

Strings:

"Design to fabrication" AND Construction [Abstract: "design to fabrication"] AND [Abstract: construction... (Articles/Chapters – 0)

"Design to fabrication" AND Construction [Publication Title: "design to fabrication"] AND [Publication T... (Articles/Chapters – 0)

"Design to fabrication" AND Construction [Keywords: "design to fabrication"] AND [Keywords: construction... (Articles/Chapters – 0)

(Abstract, Publication title, Keywords)

Filters Applied: Publication date

Include: All content – (Accepted Articles, Backfiles)

Narrow by: Content type: Articles and Chapters

Publication date: All dates

Studies list: This search did not match any articles

Appendix C - Forms for Conducting the Systematic Review: SCOPUS

Form code: C21b

Source: http://www.sbu.unicamp.br/ Base de Dados

SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date:2016/Nov15

Keywords:BIM/Fabrication

Strings: BIM AND Fabrication (Article Title, Abstract, Keywords)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article

Subject Areas: Engineering (28);Computer Science (9);Arts and Humanities (6);Social Sciences (1)

Refine

(TITLE-ABS-KEY(BIM) AND TITLE-ABS-KEY(Fabrication)) AND DOCTYPE(ar) AND SUB AREA(MULT OR CENG OR CHEM OR COMP OR EART OR ENER OR ENGI OR ENVI OR MATE OR MATH OR PHYS OR MULT OR ARTS OR BUSI OR DECI OR ECON OR PSYC OR SOCI) AND PUBYEAR > 1996 AND (EXCLUDE(SUBJAREA,"BUSI") OR EXCLUDE(SUBJAREA,"ENER") OR EXCLUDE(SUBJAREA,"ENVI"))

Studies list:

1 Gobin, T., Andraos, S., Schwartz, T.,An Art of Connectivity, ,Architectural Design,2016
2 Fok, W.W., Picon, A.,The Ownership Revolution, ,Architectural Design,2016
3 Merschbrock, C., Nordahl-Rolfsen, C.,BIM technology acceptance among reinforcement workers - The case of oslo airport's terminal 2, ,Journal of Information Technology in Construction,2016
4 Nahangi, M., Haas, C.T., West, J., Walbridge, S.,Automatic Realignment of Defective Assemblies Using an Inverse Kinematics Analogy, ,Journal of Computing in Civil Engineering,2016
5 Bryan, B., Grosman, H.,Drawing in time: Processes of design and fabrication, ,Architectural Design,2016
6 Chi, H.-L., Wang, J., Wang, X., Truijens, M., Yung, P.,A Conceptual Framework of Quality-Assured Fabrication, Delivery and Installation Processes for Liquefied Natural Gas (LNG) Plant Construction, ,Journal of Intelligent and Robotic Systems: Theory and Applications,2015
7 Chen, Z.-R., Lim, C.-K., Shao, W.-Y.,Comparisons of practice progress of digital design and fabrication in free-form architecture, ,Journal of Industrial and Production Engineering,2015
8 McGinley, T.,A morphogenetic architecture for intelligent buildings, ,Intelligent Buildings International,2015
9 Getz, J., Saenz, J.,Unified workflow: Better BIM = better designs, ,Engineered Systems,2015
10 Goulding, J.S., Rahimian, F.P.,Design creativity: Future directions for integrated visualisation, ,Archnet-IJAR,2015
11 Abdul Shukor, S.A., Wong, R., Rushforth, E., Basah, S.N., Zakaria, A.,3D terrestrial laser scanner for managing existing building, ,Jurnal Teknologi,2015

12 Goulding, J.S., Rahimian, F.P., Wang, X.,Virtual reality-based cloud BIM platform for integrated AEC projects, ,Journal of Information Technology in Construction,2014
13 Bosché, F., Guillemet, A., Turkan, Y., Haas, C.T., Haas, R.,Tracking the built status of MEP works: Assessing the value of a Scan-vs-BIM system, ,Journal of Computing in Civil Engineering,2014
14 Clevenger, C.M., Khan, R.,Impact of BIM-enabled design-to-fabrication on building delivery, ,Practice Periodical on Structural Design and Construction,2014
15 Luth, G.P., Schorer, A., Turkan, Y.,Lessons from using BIM to increase design-construction integration, ,Practice Periodical on Structural Design and Construction,2014
16 Cho, Y.S., Lee, S.I., Bae, J.S.,Reinforcement placement in a concrete slab object using structural building information modeling, ,Computer-Aided Civil and Infrastructure Engineering,2014
17 Knippers, J.,Integrative design in the digital process | [Integriertes Entwerfen im digitalen Prozess], ,Bautechnik,2014
18 Maccioni, A., Keen, J., Weir, A., Winslow, P.,Jumping in at the deep end: How a small company applied BIM to a huge project, ,Structural Engineer,2013
19 Eley, D., Aldwinckle, G.,Digital design collaboration and complex fabrication, ,Structural Engineer,2013
20 Karaman, S., Chen, S., Ratnagaran, B.,Three-dimensional parametric data exchange for curved steel bridges, ,Transportation Research Record,2013
21 Ceccato, C.,Material articulation: Computing and constructing continuous differentiation, ,Architectural Design,2012
22 Jensen, F.,Design and construction of the danish cancer center, ,International Journal of Space Structures,2010
23 Sacks, R., Kaner, I., Eastman, C.M., Jeong, Y.-S.,The Rosewood experiment - Building information modeling and interoperability for architectural precast facades, ,Automation in Construction,2010
24 Wong, K.,Reconstructing nature, ,Computer Graphics World,2009
25 Jeong, Y.-S., Eastman, C.M., Sacks, R., Kaner, I.,Benchmark tests for BIM data exchanges of precast concrete, ,Automation in Construction,2009
26 Ireland, B.,Barriers to BIM, ,EC and M: Electrical Construction and Maintenance,2009
27 Robinson, C.,Structural BIM in action, ,Structural Engineer,2008
28 Khanzode, A., Fischer, M., Reed, D.,Benefits and lessons learned of implementing Building Virtual Design and Construction (VDC) technologies for coordination of Mechanical, Electrical, and Plumbing (MEP) systems on a large Healthcare project, ,DocumentElectronic Journal of Information Technology in Construction,2008
29 Gonchar, J.,Transformative tools start to take hold, ,ENR (Engineering News-Record),2007

Study	Exclusions criteria	Status
1	4	Excluded

2	4	Excluded
3	8	Excluded
4	8	Excluded
5	4	Excluded
6		
7	2	Excluded
8	8	Excluded
9	2	Excluded
10	8	Excluded
11	8	Excluded
12		
13	1	Excluded
14	8	Excluded
15	8	Excluded
16	8	Excluded
17	3	Excluded
18	2	Excluded
19	2	Excluded
20		
21	4	Excluded
22	8	Excluded
23		
24	2	Excluded
25	8	Excluded
26	2	Excluded
27	2	Excluded
28		
29	2	Excluded

Form code: C22b

Source: http://www.sbu.unicamp.br/ Base de Dados SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: Building Information Modeling/ Fabrication

Strings:

Building Information Modeling AND Fabrication *(Article Title, Abstract, Keywords)*

Limit to:

Date Range (inclusive) Published 1997 to Present

Document Type: Article Book

Subject Areas: Engineering (30);Computer Science (7);Arts and Humanities (7)

Studies list:

1 Gobin, T., Andraos, S., Schwartz, T.,An Art of Connectivity, ,Architectural Design,2016
2 Fok, W.W., Picon, A.,The Ownership Revolution, ,Architectural Design,2016
3 Sun, J.,Template-guided visual try-in evaluation for nasal prosthesis modeling, ,Rapid Prototyping Journal,2016
4 Merschbrock, C., Nordahl-Rolfsen, C.,BIM technology acceptance among reinforcement workers - The case of oslo airport's terminal 2, ,Journal of Information Technology in Construction,2016
5 Bryan, B., Grosman, H.,Drawing in time: Processes of design and fabrication, ,Architectural Design,2016
6 Walliss, J., Rahmann, H.,Landscape architecture and digital technologies: Re-conceptualising design and making (Book), , Landscape Architecture and Digital Technologies: Re-Conceptualising Design and Making,2016
7 McGinley, T.,A morphogenetic architecture for intelligent buildings, ,Intelligent Buildings International,2015
8 Chen, Z.-R., Lim, C.-K., Shao, W.-Y.,Comparisons of practice progress of digital design and fabrication in free-form architecture, , Journal of Industrial and Production Engineering,2015
9 Abdul Shukor, S.A., Wong, R., Rushforth, E., Basah, S.N., Zakaria, A.,3D terrestrial laser scanner for managing existing building, , Jurnal Teknologi,2015
10 Getz, J., Saenz, J.,Unified workflow: Better BIM = better designs, ,Engineered Systems,2015
11 Goulding, J.S., Rahimian, F.P., Wang, X.,Virtual reality-based cloud BIM platform for integrated AEC projects, , Journal of Information Technology in Construction,2014
12 Clevenger, C.M., Khan, R.,Impact of BIM-enabled design-to-fabrication on building delivery, ,Practice Periodical on Structural Design and Construction,2014
13 Luth, G.P., Schorer, A., Turkan, Y.,Lessons from using BIM to increase design-construction integration, ,Practice Periodical on Structural Design and Construction,2014
14 Cho, Y.S., Lee, S.I., Bae, J.S.,Reinforcement placement in a concrete

slab object using structural building information modeling, ,Computer-Aided Civil and Infrastructure Engineering,2014
15 Knippers, J.,Integrative design in the digital process | [Integriertes Entwerfen im digitalen Prozess], ,Bautechnik,2014
16 Sun, J., Chen, X., Liao, H., xi, J.,Template based framework for nasal prosthesis fabrication, ,Rapid Prototyping Journal,2013
17 Karaman, S., Chen, S., Ratnagaran, B.,Three-dimensional parametric data exchange for curved steel bridges, ,Transportation Research Record,2013
18 Costa, E.C., Duarte, J.P., Coutinho, F., Krüger, M.,Generative modelling of an Albertian capital | [Modelação generativa de um capitel Albertiano], ,Arquiteturarevista,2012
19 Vatani, M., Barazandeh, F., Rahimi, A., Sanati Nezhad, A.,Distortion modeling of SL parts by classical lamination theory, ,Rapid Prototyping Journal,2012
20 Ceccato, C.,Material articulation: Computing and constructing continuous differentiation, ,Architectural Design,2012
21 Shepherd, P., Hudson, R., Hines, D.,Aviva Stadium: A parametric success, ,International Journal of Architectural Computing,2011
22 Jensen, F.,Design and construction of the danish cancer center, ,International Journal of Space Structures,2010
23 Sacks, R., Kaner, I., Eastman, C.M., Jeong, Y.-S.,The Rosewood experiment - Building information modeling and interoperability for architectural precast facades, ,Automation in Construction,2010
24 Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., Mikalauskas, S.,The use of a virtual building design and construction model for developing an effective project concept in 5D environment, ,Automation in Construction,2010
25 Wang, P., Abourizk, S.M.,Large-scale simulation modeling system for industrial construction, ,Canadian Journal of Civil Engineering,2009
26 Wong, K.,Reconstructing nature, ,Computer Graphics World,2009
27 Jeong, Y.-S., Eastman, C.M., Sacks, R., Kaner, I.,Benchmark tests for BIM data exchanges of precast concrete, ,Automation in Construction, 2009
28 Ireland, B.,Barriers to BIM, ,EC and M: Electrical Construction and Maintenance,2009
29 Khanzode, A., Fischer, M., Reed, D.,Benefits and lessons learned of implementing Building Virtual Design and Construction (VDC) technologies for coordination of Mechanical, Electrical, and Plumbing (MEP) systems on a large Healthcare project, ,Document Electronic Journal of Information Technology in Construction,2008
30 Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A., Wong, I.,Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings, ,Automation in Construction,2008
31 Gonchar, J.,Transformative tools start to take hold, ,ENR (Engineering News-Record),2007

Study	Exclusions criteria	Status

1	1	Excluded
2	1	Excluded
3	2	Excluded
4	1	Excluded
5	1	Excluded
6	2	Excluded
7	1	Excluded
8	1	Excluded
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12	1	Excluded
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14	1	Excluded
15	3	Excluded
16	2	Excluded
17	1	Excluded
18	8	Excluded
19	2	Excluded
20	1	Excluded
21	2	Excluded
22	1	Excluded
23	1	Excluded
24	6	Excluded
25	4	Excluded
26	1	Excluded
27	1	Excluded
28	1	Excluded
29	1	Excluded
30	8	Excluded
31	1	Excluded

Form code: C23b

Source: http://www.sbu.unicamp.br/ Base de Dados

SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date:2016/Nov15

Keywords:BIM/Mass Customization

Strings: BIM AND Mass Customization (Article Title, Abstract, Keywords)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(1)

Subject Areas: Engineering (1)

Studies list:

1 Farr, E.R.P., Piroozfar, P.A.E., Robinson, D.,BIM as a generic configurator for facilitation of customisation in the AEC industry, ,Automation in Construction,2014

Study	Exclusions criteria	Status
1		

Form code: C24b

Source: http://www.sbu.unicamp.br/ Base de Dados

SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date:2016/Nov15

Keywords:Building Information Modeling/Mass Customization

Strings:

Building Information Modeling AND Mass Customization *(Article Title, Abstract, Keywords)*

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(2)

Subject Areas: Engineering (2)

Studies list:

1 Xie, J., Chen, X., Hu, Y.,Dynamic modeling of product family in mass customization, ,Journal of Computational Information Systems,2005

2 Lin, Y., Ma, D., Yan, J.,PLM-based product platform - The 21st century product R and D strategy for MC, ,Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering,2004

Study	Exclusions criteria	Status
1	2	Excluded
2	2	Excluded

Form code: C25b

Source: http://www.sbu.unicamp.br/

Base de Dados SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: BIM/ Digital Fabrication

Strings: BIM AND Digital Fabrication (Article Title, Abstract, Keywords)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(9);Book Chapter(2)

Subject Areas:Engineering (10) ;Computer Science (2);Arts and Humanities (1);Social Sciences (3)

Business Management and Accounting(1)

Studies list:

1 Gobin, T., Andraos, S., Schwartz, T.,An Art of Connectivity, ,Architectural Design,2016
2 Chen, Z.-R., Lim, C.-K., Shao, W.-Y.,Comparisons of practice progress of digital design and fabrication in free-form architecture, ,Journal of Industrial and Production Engineering,2015
3 McGinley, T.,A morphogenetic architecture for intelligent buildings, ,Intelligent Buildings International,2015
4 Goulding, J.S., Rahimian, F.P.,Design creativity: Future directions for integrated visualisation, ,Archnet-IJA1,2015
5 Knippers, J.,Integrative design in the digital process | [Integriertes Entwerfen im digitalen Prozess], ,Bautechnik,2014
6 Eley, D., Aldwinckle, G.,Digital design collaboration and complex fabrication, ,Structural Engineer,2013
7 Maccioni, A., Keen, J., Weir, A., Winslow, P.,Jumping in at the deep end: How a small company applied BIM to a huge project, ,Structural Engineer,2013
8 Sass, L.,Direct building manufacturing of homes with digital fabrication (Book Chapter), ,Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education,2012
9 Ostwald, M.J.,Systems and enablers: Modeling the impact of contemporary computational methods and technologies on the design process (Book Chapter), ,Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education,2012
10 Wong, K.,Reconstructing nature, ,Computer Graphics World,2009
11 Sawyer, T.,Leading off with a hit, new yankees home scores big, ,ENR (Engineering News-Record),2009

Study	Exclusions criteria	Status
1	1	Excluded

2	1	Excluded
3	1	Excluded
4	1	Excluded
5	3	Excluded
6	1	Excluded
7	1	Excluded
8	2	Excluded
9	2	Excluded
10	1	Excluded
11	2	Excluded

Form code: C26b

Source: http://www.sbu.unicamp.br/ Base de Dados

SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: Building Information Modeling/ Digital Fabrication

Strings: Building Information Modeling AND Digital Fabrication *(Article Title, Abstract, Keywords)*

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(8);Book Chapter(2)

Subject Areas:Engineering (9) ;Computer Science (2);Arts and Humanities (1);Social Sciences (3)

Studies list:

1 Gobin, T., Andraos, S., Schwartz, T.,An Art of Connectivity, ,Architectural Design,2016
2 McGinley, T.,A morphogenetic architecture for intelligent buildings, ,Intelligent Buildings International,2015
3 Chen, Z.-R., Lim, C.-K., Shao, W.-Y.,Comparisons of practice progress of digital design and fabrication in free-form architecture, ,Journal of Industrial and Production Engineering,2015
4 Goulding, J.S., Rahimian, F.P.,Design creativity: Future directions for integrated visualisation, ,Archnet-IJAR,2015
5 Knippers, J.,Integrative design in the digital process | [Integriertes Entwerfen im digitalen Prozess], ,Bautechnik,2014
6 Sun, J., Chen, X., Liao, H., xi, J.,Template based framework for nasal

prosthesis fabrication, ,Rapid Prototyping Journal,2013
7 Sass, L.,Direct building manufacturing of homes with digital fabrication (Book Chapter), ,Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education,2012
8 Ostwald, M.J.,Systems and enablers: Modeling the impact of contemporary computational methods and technologies on the design process (Book Chapter), ,Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education,2012
9 Costa, E.C., Duarte, J.P., Coutinho, F., Krüger, M.,Generative modelling of an Albertian capital | [Modelação generativa de um capitel Albertiano], ,Arquiteturarevista,2012
10 Wong, K.,Reconstructing nature, ,Computer Graphics World,2009

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded
4	1	Excluded
5	3	Excluded
6	1	Excluded
7	1	Excluded
8	1	Excluded
9	1	Excluded
10	1	Excluded

Form code: C27b

Source: http://www.sbu.unicamp.br/ Base de Dados

SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: Design to Fabrication/ Architecture

Strings: Design to Fabrication AND Architecture *(Article Title, Abstract, Keywords)*

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(5)

Subject Areas: Engineering (3) Computer Science (1) Arts and Humanities (1) Materials Sciences (1) Mathematics (1)

Studies list:

1 Sousa, J.P., Xavier, J.P.,Symmetry-based generative design and

fabrication: A teaching experiment, ,Automation in Construction,2015
2 Stavrić, M., Wiltsche, A.,Three-dimensional ornamental structures based on the wallpaper groups in architecture, ,Journal for Geometry and Graphics,2012
3 Pottmann, H.,Architectural geometry as design knowledge, ,Architectural Design,2010
4 Tummala, R.R., Swaminathan, M., Tentzeris, M.M., (...), Liu, F., Raj, P.M.,The SOP for miniaturized, mixed-signal computing, communication, and consumer systems of the next decade, ,IEEE Transactions on Advanced Packaging,2004
5 Sitte, J., Körner, T., Rückert, U.,Local cluster neural net analog VLSI design, ,Neurocomputing,1998

Study	Exclusions criteria	Status
1	8	Excluded
2		
3	2	Excluded
4	8	Excluded
5	4	Excluded

Form code: C28b

Source: http://www.sbu.unicamp.br/ Base de Dados SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: Design to Fabrication/ Manufactur*

Strings: Design to Fabrication AND Manufactur* *(Article Title, Abstract, Keywords)*

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(7)

Subject Areas:Engineering (6) ;Computer Science (1);Materials Sciences (1);Energy (1);Physics and Astronomy (2)

Studies list:

1 Gattas, J.M., You, Z.,Design and digital fabrication of folded sandwich structures, ,Automation in Construction,2016
2 Duro-Royo, J., Mogas-Soldevila, L., Oxman, N.,Flow-based fabrication: An integrated computational workflow for design and digital additive manufacturing of multifunctional heterogeneously structured objects, ,CAD Computer Aided Design,2015
3 Yuan, Y., Kazimi, M.S., Hejzlar, P.,Thermomechanical performance of

high-power-density annular fuel, ,Nuclear Technology,2007
4 Yu, H., Balogun, O., Li, B., Murray, T.W., Zhang, X.,Fabrication of three-dimensional microstructures based on singled-layered SU-8 for lab-on-chip applications, ,Sensors and Actuators, A: Physical,2006
5 Yu, H., Li, B., Zhang, X.,Flexible fabrication of three-dimensional multi-layered microstructures using a scanning laser system, ,Sensors and Actuators, A: Physical,2006
6 Tummala, R.R., Swaminathan, M., Tentzeris, M.M., (...), Liu, F., Raj, P.M.,The SOP for miniaturized, mixed-signal computing, communication, and consumer systems of the next decade, ,IEEE Transactions on Advanced Packaging,2004
7 Wang, F.-C., Plancarte, J., Wright, P.K., Fabbrizio, V., Kramer, A.,Industrial design to rapid mold making for accelerated time-to-market of consumer electronic products, ,DocumentAmerican Society of Mechanical Engineers, Manufacturing Engineering Division, MED,1999

Study	Exclusions criteria	Status
1		
2		
3	2	Excluded
4	4	Excluded
5	8	Excluded
6	1	Excluded
7	2	Excluded

Form code: C29b

Source: http://www.sbu.unicamp.br/ Base de Dados SCOPUS https://www-scopus-com.ez88.periodicos.capes.gov.br/home.uri

Search date: 2016/Nov15

Keywords: Design to Fabrication/ Construction

Strings: Design to Fabrication AND Construction *(Article Title, Abstract, Keywords)*

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(2)

Subject Areas: Engineering (2) Arts and Humanities (2)

Studies list:

1 Clevenger, C.M., Khan, R.,Impact of BIM-enabled design-to-fabrication on building delivery, ,Practice Periodical on Structural Design and Construction,2014

2 Pottmann, H.,Architectural geometry as design knowledge, ,Architectu Design,2010

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded

Appendix D - Forms for Conducting the Systematic Review: Web of Science

Form code: C41b

Source: http://www.sbu.unicamp.br/ □ Bases de Dados □ pesquisar □ w □ Web of Science

Search date: 2016/Nov22

Keywords: BIM/Fabrication

Strings:BIM Fabrication = (BIM AND Fabrication)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(16)

*Subject Areas:*ENGINEERING CIVIL (9);CONSTRUCTION BUILDING TECHNOLOGY (4);COMPUTER SCIENCE INTERDISCIPLINARY APPLICATIONS (3);TRANSPORTATION SCIENCE TECHNOLOGY (2);COMPUTER SCIENCE ARTIFICIAL

INTELLIGENCE (2)

Studies list:

1 Nahangi, Mohammad; Haas, Carl T.; West, Jeffrey; et al,Automatic Realignment of Defective Assemblies Using an Inverse Kinematics Analogy,Volume: 30 Edição: 2,JOURNAL OF COMPUTING IN CIVIL ENGINEERING,2016

2 Merschbrock, Christoph; Nordahl-Rolfsen, Christian,BIM TECHNOLOGY ACCEPTANCE AMONG REINFORCEMENT WORKERS - THE CASE OF OSLO AIRPORT'S TERMINAL 2,Volume: 21 Páginas: 1-12,JOURNAL OF INFORMATION TECHNOLOGY IN CONSTRUCTION,2016

3 Nahangi, Mohammad; Haas, Carl T.,Skeleton-based discrepancy feedback for automated realignment of industrial assemblies,Volume: 61 Páginas: 147-,AUTOMATION IN CONSTRUCTION,2016

4 Chi, Hung-Lin; Wang, Jun; Wang, Xiangyu; et al.,A Conceptual Framework of Quality-Assured Fabrication, Delivery and Installation Processes for Liquefied Natural Gas (LNG) Plant Construction,Volume: 79 Edição: 3-4 ,JOURNAL OF INTELLIGENT & ROBOTIC SYSTEMS ,2015

5 Spallone, Roberta,RECONSTRUCTION, MODELING, ANIMATION AND DIGITAL FABRICATION OF 'ARCHITECTURES ON PAPER'. TWO IDEAL HOUSES BY CARLO MOLLINO,Volume: 5 Edição: 1 Páginas: 101-114 ,SCIRES-IT-SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY ,2015

6 Nahangi, Mohammad; Haas, Carl T.,Automated 3D compliance checking in pipe spool fabrication,Volume: 28 Edição: 4 Páginas: 360-369 ,ADVANCED ENGINEERING INFORMATICS,2014

7 Bosche, Frederic; Guillemet, Adrien; Turkan, Yelda; et al.,Tracking the Built Status of MEP Works: Assessing the Value of a Scan-vs.-BIM System,Volume: 28 Edição: 4 ,JOURNAL OF COMPUTING IN CIVIL ENGINEERING ,2014

8 Ren, Liling; Kang, Yunqing; Browne, Christopher; et al,Fabrication, vascularization and osteogenic properties of a novel synthetic biomimetic induced membrane for the treatment of large bone defects,Volume: 64 Páginas: 173-182 ,BONE,2014

9 Knippers, Jan,Integrative design in the digital process,Volume: 91 Edição: 4 Páginas: 257-261 ,BAUTECHNIK,2014

10 Park, Sungjin; Lim, Jai Dong; Peranantham, Pazhanisami; et al.,Binary mask designs with single- and double-layer absorber stacks for extreme ultraviolet lithography and actinic inspection,Volume: 53 Edição: 4 Páginas: A42-A47 ,APPLIED OPTICS,2014

11 Cho, Young Sang; Lee, Seung Il; Bae, Jun Seo,Reinforcement Placement in a Concrete Slab Object Using Structural Building Information Modeling,Volume: 29 Edição: 1 Edição especial: SI Páginas: 47-59 ,COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING ,2014

12 Ashley, John F.; Bowman, Christopher N.; Davis, Robert H.,Hydrodynamic separation of particles using pinched-flow fractionation,Volume: 59 Edição: 9 Páginas: 3444-3457 ,AICHE JOURNA,2013
13 Karaman, S. Gokhan; Chen, Stuart S.; Ratnagaran, Benny J.,Three-Dimensional Parametric Data Exchange for Curved Steel Bridges,Edição: 2331 Páginas: 27-34 ,TRANSPORTATION RESEARCH RECORD,2013
14 Ceccato, Cristiano,Material Articulation: Computing and Constructing Continuous Differentiation,Volume: 82 Edição: 2 Edição especial: SI Páginas: 96-,ARCHITECTURAL DESIGN ,2012
15 Sacks, Rafael; Kaner, Israel; Eastman, Charles M.; et al.,The Rosewood experiment - Building information modeling and interoperability for architectural precast facades,Volume: 19 Edição: 4 Edição especial: SI Páginas: 419-432 ,AUTOMATION IN CONSTRUCTION ,2010
16 Jeong, Y. -S.; Eastman, C. M.; Sacks, R.; et al.,Benchmark tests for BIM data exchanges of precast concrete,Volume: 18 Edição: 4 Páginas: 469-484 ,AUTOMATION IN CONSTRUCTION ,2009

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	8	Excluded
4	1	Excluded
5	4	Excluded
6	8	Excluded
7	1	Excluded
8	4	Excluded
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12	4	Excluded
13	1	Excluded
14	1	Excluded
15	1	Excluded
16	1	Excluded

Form code: C42b

Source: http://www.sbu.unicamp.br/ → Bases de Dados → pesquisar → w → Web of Science

Search date: 2016/Nov22

Keywords: “Building Information Modeling”/Fabrication

Strings:“Building Information Modeling” Fabrication = (“Building Information Modeling” AND Fabrication)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: *Article(12);*PROCEEDINGS PAPER (1)

Subject Areas:

ENGINEERING CIVIL (10);ENGINEERING INDUSTRIAL (1);CONSTRUCTION BUILDING TECHNOLOGY (6);COMPUTER SCIENCE INTERDISCIPLINARY APPLICATIONS (2);TRANSPORTATION SCIENCE TECHNOLOGY (2)

Studies list

1 Nahangi, Mohammad; Haas, Carl T.; West, Jeffrey; et al.,Automatic Realignment of Defective Assemblies Using an Inverse Kinematics Analogy,Volume: 30 Edição: 2 ,JOURNAL OF COMPUTING IN CIVIL ENGINEERING,2016

2 Merschbrock, Christoph; Nordahl-Rolfsen, Christian,BIM TECHNOLOGY ACCEPTANCE AMONG REINFORCEMENT WORKERS - THE CASE OF OSLO AIRPORT'S TERMINAL 2,Volume: 21 Páginas: 1-12 ,JOURNAL OF INFORMATION TECHNOLOGY IN CONSTRUCTION ,2016

3 Chi, Hung-Lin; Wang, Jun; Wang, Xiangyu; et al.,A Conceptual Framework of Quality-Assured Fabrication, Delivery and Installation Processes for Liquefied Natural Gas (LNG) Plant Construction,Volume: 79 Edição: 3-4 Edição especial: SI Páginas: 433-448 ,JOURNAL OF INTELLIGENT & ROBOTIC SYSTEMS,2015

4 Nahangi, Mohammad; Yeung, Jamie; Haas, Carl T.; et al,Automated assembly discrepancy feedback using 3D imaging and forward kinematics,Volume: 56 Páginas: 36-46 ,AUTOMATION IN CONSTRUCTION,2015

5 Knippers, Jan,Integrative design in the digital process,Volume: 91 Edição: 4 Páginas: 257-261 ,BAUTECHNIK,2014

6 Cho, Young Sang; Lee, Seung Il; Bae, Jun Seo,Reinforcement Placement in a Concrete Slab Object Using Structural Building Information Modeling,Volume: 29 Edição: 1 Edição especial: SI Páginas: 47-59 ,COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING,2014

7 Karaman, S. Gokhan; Chen, Stuart S.; Ratnagaran, Benny J.,Three-Dimensional Parametric Data Exchange for Curved Steel Bridges,Edição: 2331 Páginas: 27-34 ,TRANSPORTATION RESEARCH RECORD,2013

8 Lee, Ghang; Kim, Seonwoo,Case Study of Mass Customization of Double-Curved Metal Facade Panels Using a New Hybrid Sheet Metal Processing Technique,Volume: 138 Edição: 11 Páginas:1322-1330 ,JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT-ASCE ,2012

9 Ceccato, Cristiano,Material Articulation: Computing and Constructing Continuous Differentiation,Volume: 82 Edição: 2 Edição especial: SI Páginas: 96-103 ,ARCHITECTURAL DESIGN ,2012

10 Sacks, Rafael; Kaner, Israel; Eastman, Charles M.; et al.,The Rosewood experiment - Building information modeling and interoperability for architectural precast facades,Volume: 19 Edição: 4 Edição especial: SI Páginas: 419-432 ,AUTOMATION IN CONSTRUCTION,2010

11 Popov, Vladimir; Juocevicius, Virgaudas; Migilinskas, Darius; et al,The use of a virtual building design and construction model for developing an effective project concept in 5D environment,Volume: 19 Edição: 3 Edição especial: SI Páginas: 357-367 ,AUTOMATION IN CONSTRUCTION,2010

12 Jeong, Y. -S.; Eastman, C. M.; Sacks, R.; et al.,Benchmark tests for BIM data exchanges of precast concrete,Volume: 18 Edição: 4 Páginas: 469-484 ,AUTOMATION IN CONSTRUCTION,2009

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded
4	4	Excluded
5	3	Excluded
6	1	Excluded
7	1	Excluded
8		
9	1	Excluded
10	1	Excluded
11	1	Excluded

12	1	Excluded

Form code: C43b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w Web of Science

Search date: 2016/Nov22

Keywords: BIM/“Mass Customization”

Strings:BIM “Mass Customization” = (BIM AND “Mass Customization”)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(2)

Subject Areas: Engineering Civil (1)Construction Building Technology (1)Business(1)

Studies list:

1 Cheung, F. K. T.; Kurul, E.; Oti, A. H.,A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales,Volume: 34 Edição: 4-5 Edição especial: SI Páginas: 335-352 ,CONSTRUCTION MANAGEMENT AND ECONOMICS ,2016

2 Farr, Eric R. P.; Piroozfar, Poorang A. E.; Robinson, Dexter,BIM as a generic configurator for facilitation of customisation in the AEC industry,Volume: 45 Páginas: 119-125 ,AUTOMATION IN CONSTRUCTION,2014

Study	Exclusions criteria	Status
1		
2	1	Excluded

Form code: C44b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w Web of Science

Search date: 2016/Nov22

Keywords: “Building Information Modeling”/“Mass Customization”

Strings:“Building Information Modeling” Fabrication = (“Building Information Modeling” AND “Mass Customization”)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(1) PROCEEDINGS PAPER (1)

Studies list:

1 Hu, Ming,PERFORMANCE-BASED DESIGN,Páginas: 727-729 ,PROCEEDINGS OF THE 18TH INTERNATIONAL CONFERENCE ON COMPUTER-AIDED ARCHITECTURAL DESIGN RESEARCH IN ASIA (CAADRIA 2013): OPEN SYSTEMS ,2013

2 Lee, Ghang; Kim, Seonwoo,Case Study of Mass Customization of Double-Curved Metal Facade Panels Using a New Hybrid Sheet Metal Processing Technique,Volume: 138 Edição: 11 Páginas:1322-1330 ,JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT-ASCE,2012

Study	Exclusions criteria	Status
1	2	Excluded
2	1	Excluded

Form code: C45b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w Web of Science

Search date: 2016/Nov22

Keywords: BIM/“Digital Fabrication”

Strings:BIM “Digital Fabrication” = (BIM AND “Digital Fabrication”)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword

Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(2)

Studies list:

1 Spallone, Roberta,RECONSTRUCTION, MODELING, ANIMATION AND DIGITAL FABRICATION OF 'ARCHITECTURES ON PAPER'. TWO IDEAL HOUSES BY CARLO MOLLINO,Volume: 5 Edição: 1 Páginas: 101-114 ,SCIRES-IT-SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY ,2015

2 Wu, Tienyu; Jeng, Taysheng,Reforming Design Studios Experiments in integrating bim, parametric design, digital fabrication, and interactive technology,VOL 1: DIGITAL PHYSICALITY Páginas: 49- ,30th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe),2012

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded

Form code: C46b

Source: http://www.sbu.unicamp.br/ □ Bases de Dados □ pesquisar □ w □ Web of Science

Search date: 2016/Nov22

Keywords: Building Information Modeling/Digital Fabrication

Strings:“Building Information Modeling” “Digital Fabrication” = (“Building Information Modeling” AND “Digital Fabrication”) (Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type:PROCEEDINGS PAPER (3)

Studies list:

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(CAADRIA 2015): EMERGING EXPERIENCES IN THE PAST, PRESENT AND FUTURE OF DIGITAL ARCHITECTURE,2015
2 Wu, Tienyu; Jeng, Taysheng,Reforming Design Studios Experiments in integrating bim, parametric design, digital fabrication, and interactive technology,VOL 1: DIGITAL PHYSICALITY Páginas: 49-,30th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe),2012
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Study	Exclusions criteria	Status
1	2	Excluded
2	8	Excluded
3	2	Excluded

Form code: C47b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w Web of Science

Search date: 2016/Nov22

Keywords: “Design to Fabrication”/Architecture

Strings:“Design to Fabrication” Architecture = (“Design to Fabrication” AND Architecture)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(3)

Studies list:

1 Sousa, Jose Pedro; Xavier, Joao Pedro,Symmetry-based generative design and fabrication: A teaching experiment,Volume: 51 Páginas: 113-123 ,AUTOMATION IN CONSTRUCTION,2015
2 Tummala, RR; Swaminathan, M; Tentzeris, MM; et al,The SOP for miniaturized, mixed-signal computing, communication, and consumer systems of the next decade,Volume: 27 Edição: 2 Páginas: 250-267 ,IEEE

TRANSACTIONS ON ADVANCED PACKAGING,2004

3 Sitte, J; Korner, T; Ruckert, U,Local cluster neural net analog VLSI design,Volume: 19 Edição: 1-3 Páginas: 185-197 , NEUROCOMPUTING,1998

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded

Form code: C48b

Source: http://www.sbu.unicamp.br/ □ Bases de Dados □ pesquisar □ w □ Web of Science

Search date: 2016/Nov22

Keywords: “Design to Fabrication”/Manufactur*

Strings:“Design to Fabrication” Manufactur* = (“Design to Fabrication” AND Manufactur*) (Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: Article(10)

Studies list:

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2 Stoeckli, Fritz; Modica, Fabio; Shea, Kristina,Designing passive dynamic walking robots for additive manufacture,Volume: 22 Edição: 5 Edição especial: SI Páginas: 842-847 ,RAPID PROTOTYPING JOURNAL,2016

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Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded
4	2	Excluded
5	8	Excluded
6		
7	2	Excluded
8	1	Excluded
9	1	Excluded
10	1	Excluded

Form code: C49b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w Web of Science

Search date: 2016/Nov22

Keywords: "Design to Fabrication"/Construction

Strings:"Design to Fabrication" Construction = ("Design to Fabrication" AND Construction)

(Topico = Titulo,Resumo, Palavras-chave de autor, Keyword Plus)

Limit to: Date Range (inclusive) Published 1997 to Present

Document Type: PROCEEDINGS PAPER (2)

Subject Areas: ARCHITECTURE (2)EDUCATION EDUCATIONAL RESEARCH (1)

Studies list:

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Study	Exclusions criteria	Status
1	2	Excluded
2	8	Excluded

Appendix E - Forms for Conducting the Systematic Review: ASCE library

Form code: C61b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar w ASCE LIBRARY (American Society of Civil Engineers

Search date: 2016/Nov24

Keywords: BIM/Fabrication

Strings:BIM AND Fabrication (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations)

Search for "[Anywhere: bim] AND [Anywhere: fabrication] AND [Anywhere: fabrication] AND [Publication Date: (01/01/1997 TO12/31/2016)] AND [PubType: Article]"

Publication Date: From: Jan 1997 to: December 2016

Publication Title(s):All Journals

Studies list:

1 Caroline M. Clevenger and Ricardo Khan,Impact of BIM-Enabled Design-to-Fabrication on Building Delivery,Vol. 19, No. 1, pp. 122-128, Practice Periodical on Structural Design and Construction,2014

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Construction,2014
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System Implementation: Case Study,Vol. 139, No. 4, pp. 445-455,Journal of

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Form code: C64b

Source: http://www.sbu.unicamp.br/ □ Bases de Dados □ pesquisar □ w □ ASCE LIBRARY (American Society of Civil Engineers http://ascelibrary-org.ez88.periodicos.capes.gov.br/action/showPublications?pubType=journal&mobileUi=0

Search date:2016/Nov24

Keywords: Building Information Modeling"/"Mass Customization"

Strings:"Building Information Modeling" AND "Mass Customization" (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations)

Search for "[Anywhere: "building information modeling"] AND [Anywhere: "mass customization"] AND [Publication Date: (01/01/1997 TO 12/31/2016)] AND [PubType: Article]"

Publication Date: From: Jan 1997 to: December 2016

Publication Title(s): All Journals

Studies list:

1 Ghang Lee and Seonwoo Kim,Case Study of Mass Customization of Double-Curved Metal Façade Panels Using a New Hybrid Sheet Metal Processing Technique,Vol. 138, No. 11, pp. 1322-1330,Journal of Construction Engineering and Management,2012

2 Gerhard Girmscheid and Thomas Rinas,Business Design

Modeling for Industrialization in Construction: Cooperative Approach,Vol. 18, No. 2, pp. 164-175,Journal of Architectural Engineering,2012

3 Nawari O. Nawari,BIM Standard in Off-Site Construction,Vol. 18, No. 2, pp. 107-113,Journal of Architectural Engineering,2012

4 Mohammed Arif, Jack Goulding, and Farzad Pour Rahimian,Promoting Off-Site Construction: Future Challenges and Opportunities,Vol. 18, No. 2, pp. 75-78,Journal of Architectural Engineering,2012

5 Hisham Said,Prefabrication Best Practices and Improvement Opportunities for Electrical Construction,Vol. 141, No. 12,Journal of Construction Engineering and Management,2015

6 Yujie Lu, Yongkui Li, Miroslaw Skibniewski, Zhilei Wu, Runshi Wang, and Yun Le,Information and Communication Technology Applications in Architecture, Engineering, and Construction Organizations: A 15-Year Review,Vol. 31, No. 1,Journal of Management in Engineering,2015

7 Yacine Rezgui and John Miles,Exploring the Potential of SME Alliances in the Construction Sector,Vol. 136, No. 5, pp. 558-567,Journal of Construction Engineering and Management,2010

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded
4	1	Excluded
5	1	Excluded
6	1	Excluded
7		

Form code: C65b

Source:http://www.sbu.unicamp.br/

Bases de Dados pesquisar w ASCE

LIBRARY (American Society of Civil Engineers

http://ascelibrary-org.ez88.periodicos.capes.gov.br/action/showPublications?pubType=journal&mobileUi=0

Search date: 2016/Nov24

Keywords:BIM “Digital Fabrication”

Strings:BIM AND “Digital Fabrication” (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations)

Search for "[Anywhere: bim] AND [Anywhere: "digital fabrication"] AND [Publication Date: (01/01/1997 TO 12/31/2016)] AND[PubType: Article]"

Publication Date: From: Jan 1997 to: December 2016

Publication Title(s): All Journals

Studies list:

1 Rolando Chacón and Sergio Oller,Designing Experiments Using Digital Fabrication in Structural Dynamics,,Journal of Professional Issues in Engineering Education and Practice,2016

2 Ashwin Mahalingam, Amit Kumar Yadav, and Jarjana Varaprasad,Investigating the Role of Lean Practices in Enabling BIM Adoption: Evidence from Two Indian Cases,Vol. 141, No. 7,Journal of Construction Engineering and Management,2015

3 Tober C. Francom and Mounir El Asmar,Project Quality and Change Performance Differences Associated with the Use of Building Information Modeling in Design and Construction Projects: Univariate and Multivariate Analyses,Vol. 141, No. 9, Journal of Construction Engineering and Management,2015

4 David C. Kent and Burcin Becerik-Gerber,Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery,Vol. 136, No. 8, pp. 815-825,Journal of Construction Engineering and Management ,2010

5 Craig Schwitter and Cristobal Correa,American Beauty,Vol. 82, No. 2, pp. 46-55,Civil Engineering Magazine Archive ,2012

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	8	Excluded
4	8	Excluded
5	2	Excluded

Form code: C66b

Source:http://www.sbu.unicamp.br/ Bases de Dados pesquisar w ASCE LIBRARY (American Society of Civil Engineers

Search date: 2016/Nov24

Keywords: “Building Information Modeling” “Digital Fabrication”

Strings:“Building Information Modeling” AND “Digital Fabrication” (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations)

Search for "[Anywhere: “building information modeling”] AND [Anywhere: "digital fabrication"] AND [Publication Date: (01/01/1997TO 12/31/2016)] AND [PubType: Article]"

Publication Date: From: Jan 1997 to: December 2016

Publication Title(s): All Journals

Studies list:

1 Rolando Chacón and Sergio Oller,Designing Experiments Using Digital Fabrication in Structural Dynamics,,Journal of Professional Issues in Engineering Education and Practice,2016

2 Ashwin Mahalingam, Amit Kumar Yadav, and Jarjana Varaprasad,Investigating the Role of Lean Practices in Enabling BIM Adoption: Evidence from Two Indian Cases,Vol. 141, No. 7,Journal of Construction Engineering and Management ,2015

3 Tober C. Francom and Mounir El Asmar,Project Quality and Change Performance Differences Associated with the Use of Building Information Modeling in Design and Construction Projects: Univariate and Multivariate Analyses,Vol. 141, No. 9,Journal of Construction Engineering and Management ,2015

4 David C. Kent and Burcin Becerik-Gerber,Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery,Vol. 136, No. 8, pp. 815-825,Journal of Construction Engineering and Management ,2010

5 Craig Schwitter and Cristobal Correa,American Beauty,Vol. 82, No. 2, pp. 46-55,Civil Engineering Magazine Archive ,2012

6 Sinem Korkmaz, John I. Messner, David R. Riley, and Christopher Magent,High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools,Vol. 16, No. 1, pp. 37-45,Journal of Architectural Engineering ,2010

7 Zixiang Zhou, Jie Gong, and Mengyang Guo,Image-Based 3D Reconstruction for Posthurricane Residential Building Damage Assessment,Vol. 30, No. 2,Journal of Computing in Civil Engineering ,2016

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded
3	1	Excluded
4	1	Excluded
5	1	Excluded
6	8	Excluded
7	4	Excluded

Form code: C72b

Source:http://www.sbu.unicamp.br/ □ Bases de Dados □ pesquisar □ ASCE LIBRARY (American Society of Civil Engineers

Search date: 2016/Dec/18

Keywords: “Design to Fabrication”

Strings:“Design to Fabrication” (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations). All metadata fields plus

all XML and searcheable PDF text

Publication Date: From: 1997 to: 2016

Publication Title(s): All Journals

Studies list:

1 Caroline M. Clevenger, Ricardo Khan,Impact of BIM-Enabled Design-to-Fabrication on Building Delivery, ,Practice Periodical on Structural Design and ConstructionFebruary 2014 Volume 19, Issue 1 (122 - 128) Online publication date: April 19, 2013,

2 Atul Khanzode, Martin Fischer, Steven Hamburg,Effect of Information Standards on the Design-Construction Interface:
Case Examples from the Steel Industry, ,Computing in Civil and Building Engineering (2000) (804 - 811),
3 Manu Venugopal, Charles Eastman,Rafael Sacks,Jochen Teizer,Improving the Robustness of Model Exchanges Using Product
Modeling "Concepts" for IFC Schema, ,Computing in Civil Engineering (2011) (611 - 618),
4 Engin Burak Anil,Gokhan Unal,Ozgur Kurc,Information Requirements for Design and Detailing of Reinforced Concrete
Frames in Multiuser Environments, ,Journal of Computing in Civil EngineeringJuly 2012 Volume 26, Issue 4 (465 - 477)
Online publication date: October 03, 2011,
5 J. Jupp,Technology Adoption and Management Innovation in Construction, , Computing in Civil and Building Engineering
(2014) (753 - 760),
6 William Ibbs,Commercializing Construction Research, ,Journal of Professional Issues in Engineering Volume 116, Issue 1 (1 - 8)
Online publication date: January 01, 1990,
7 Leonard J. Morse-Fortier,What's Wrong with Metal-Plate-Connected Wood-Roof Trusses?, ,Forensic Engineering
(2000) (283 - 292),
8 C. M. Eastman,Y.-S. Jeong, R. Sacks,I. Kane,Exchange Model and Exchange Object Concepts for Implementation of
National BIM Standards, ,Journal of Computing in Civil EngineeringJanuary 2010 Volume 24, Issue 1 (25 - 34)
Online publication date: December 15, 2009,
9 G. B. Sanders,T. M. Simon, B. J. Rosenbaum,W. E. Larson, J. W. Quinn, J. E. Captain, D. S. Boucher,Overcoming the Hurdles
of Incorporating In Situ Resource Utilization (IRSU) into Human Lunar Exploration, ,Earth and Space 2010: Engineering,
Science, Construction, and Operations in Challenging Environments (1308 - 1325),

Study	Exclusions criteria	Status
1	1	Excluded
2	4	Excluded
3		
4	1	Excluded
5	8	Excluded
6	4	Excluded
7	4	Excluded
8	1	Excluded
9	4	Excluded

Form code: C73b

Source: http://www.sbu.unicamp.br/ Bases de Dados pesquisar ASCE LIBRARY (American Society of Civil Engineers

Advanced Search

Search date: 2016/Dec/18

Keywords: “Design and Fabrication”

Strings:“Design and Fabrication” (Anywhere = Authors, Title, Abstracts, Keywords, Affiliations). All metadata fields plus all XML

and searcheable PDF text

Publication Date: From: 1997 to: 2016

Publication Title(s): All Journals

Studies list:

1 James B. Stauder,Matthew H. Lambros,Scott Reeve,Universal Composite Submarine Camels - Design of a Prototype,,
Ports 2013: Success through Diversification (351 - 360)
DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784413067.037 Published online: August 19, 2013,

2 Erich Oswald P.E.,Brett H. Schneider,Lucile Walgenwitz ,Information Requirements for Design and Detailing of Reinforced Concrete Frames in Multiuser Environments, ,Structures Congress 2014
(1303 - 1314)
DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784413357.115Published online: April 09, 2014,

3 Henry H. Bardakjian,Mark W. Bush,Technology Adoption and Management Innovation in Construction, ,Pipelines 2015: Recent Advances in Underground Pipeline Engineering and Construction (325 - 335) Published online: August 18, 2015,

4 An Hou, Kurt Gramoll,Design and Fabrication of CFRP Interstage Attach Fitting for Launch Vehicles, ,Journal of Aerospace Engineering Volume 12, Issue 3 (83 - 91)Online publication date: July 01, 1999
DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/(ASCE)0893-1321(1999)12:3(83)
Journal of Aerospace Engineering Vol. 12, Issue 3 (July 1999),

5 Mohamed Saafi,Design and Fabrication of FRP Grids for Aerospace and Civil Engineering Applications, ,Journal of Aerospace Engineering Volume 13, Issue 4 (144 - 149)Online publication

date: October 01, 2000,

6 Yungseop Byun, Junbeom Song, Jaenam Kim,Jinseok Jeong, Woojin Song, Beomsoo Kan,Design and Fabrication of a Scaled-Down Unmanned Quad-Tilt-Prop Personal Air Vehicle, ,Journal of Aerospace EngineeringSeptember 2015 Volume 28, Issue 5Online publication date: October 09, 2014,

7 Henry H. Bardakjian,Michael R. McReynolds,Design and Fabrication Concepts of Steel Liners for the Rehabilitation of Large-Diameter Pressure Pipelines, ,Pipelines 2016: Out of Sight, Out of Mind, Not Out of Risk (1504 - 1514) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784479957.140 Published online: July 14, 2016,

8 Cory R. Brett,Scott J. DiFiore,Dominic J. Kelly,Paul J. Cheever,Design and Fabrication of Precast Segmental Concrete Foundations in the U.S. and Erection in the Remote Arctic, ,Structures Congress 2013: Bridging Your Passion with Your Profession (991 - 1001),

9 Aly Mousaad Aly, Girma Bitsuamlak, Arindam Gan Chowdhury, and James Erwin,Design and Fabrication of a New Open Jet Electric-Fan Wall of Wind Facility for Coastal Research,,Coastal Hazards (137 - 148) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784412664.014 Published online: July 29, 2013,

10 Charles Herckis,Meeting the Evolving Challenges of the Relocation of a 90-Inch Concrete Cylinder Pipeline by the Use of a Design Build Delivery Vehicle for Hot Tapping and Plugging,,Pipelines 2016: Out of Sight, Out of Mind, Not Out of Risk (139 - 150) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784479957.013 Published online: July 14, 2016,

11 S. Mukherjee, S.Roy,Fatigue Evaluation of a Steel Orthotropic Deck for a Lift Bridge by Laboratory Testing of a Full Scale Prototype,,Structures Congress 2015 (194 - 203 DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784479117.017 Published online: April 17, 2015,

12 Jack Call, Chris Sundberg,Dimensions for Fabricated Steel Water Pipe Fittings,, DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784479957.008 Published online: July 14, 2016,

13 Chris Sundberg,Tangent Outlet Design for Welded Steel Pipe,,Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance, Doing More with Less (952 - 963) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784412480.088 Published online: November 09, 2012,

14 D. A. Wojnowski,C. R. Fischer,WilTel Technology Curtain Wall Framing Failure Investigation,,Forensic Engineering

2012: Gateway to a Safer Tomorrow (151 - 160)
DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784412640.017 Published online: January 18, 2013,
15 Nathan Wong, John Santarius, Lawrence A. Taylor, Daniel H. Garrison, John T. James,David S. McKay, Kimberly R. Kuhlman,
Decay of Reactivity in Forsterite Due to UV Radiation,,Earth and Space 2010: Engineering, Science, Construction, and
Operations in Challenging Environments (29 - 35) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/41096(366)4
Published online: April 26, 2012,
16 Edmundo R. Esquivel,Claudio H.C. Silva,Miniature Piezocone for Use in Centrifuge Testing,,Innovations and
Applications in Geotechnical Site Characterization (118 - 129)
DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/40505(285)9 Published online: April 26, 2012,
17 Jian Chen, Fook Hou Lee,Development of a deep mixing model system on centrifuge platform,, GeoCongress 2012: State
of the Art and Practice in Geotechnical Engineering (930 - 939)
dOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784412121.096 Published online: June 20, 2012,
18 Leonard J.Morse-Fortier,What's Wrong with Metal-Plate-Connected Wood-Roof Trusses?,,Forensic
Engineering (2000) (283 - 292) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/40482(280)31
Published online: April 26, 2012,
19 Rachel Sangree,Josephine V. Carstensen,Andrew T. Gaynor,Mu Zhu,James K. Guest,Topology Optimization as a
Teaching Tool for Undergraduate Education in Structural Engineering,,Structures
Congress 2015 (2632 - 2642) DOI: http://dx.doi.org.ez88.periodicos.capes.gov.br/10.1061/9780784479117.228
Published online: April 17, 2015,

Study	Exclusions criteria	Status
1	4	Excluded
2		
3	4	Excluded
4	4	Excluded
5	8	Excluded
6	4	Excluded
7	8	Excluded
8	8	Excluded
9	4	Excluded

10	2	Excluded
11	8	Excluded
12	4	Excluded
13	4	Excluded
14	4	Excluded
15	8	Excluded
16	4	Excluded
17	4	Excluded
18	1	Excluded
19	4	Excluded

Appendix F - Forms for Conducting the Systematic Review: BDTD.IBICT

Form code: C81b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/

Search date: 2016/Dec/01

Keywords: BIM Fabrication

Strings:BIM AND Fabrication (All Fields: Title, Author,subject, Network, Tag)(All Fields:BIM AND All Fields:Fabrication)

Studies list:

1 Oliveira, Marina Rodrigues,MODELAGEM VIRTUAL E PROTOTIPAGEM RÁPIDA APLICADAS EM PROJETO DE ARQUITETURA,Master Thesis,Universidade de Sao Paulo,2011

2 Bortolini, Rafaela,MODELO PARA PLANEJAMENTO E CONTROLE LOGÍSTICO DE OBRAS DE SISTEMAS PRÉ-FABRICADOS DO TIPO ENGINEER-TO-ORDER COM O USO DE BIM 4D,Master Thesis,Universidade Federal do Rio Grande do Sul,2015

3 Morais, Helen Rachel Aguiar,COMPLEXIDADE E CUSTOMIZAÇÃO EM MASSA NA ARQUITETURA CONTEMPORÂNEA, Universidade de Brasilia ,Master Thesis,Universidade de Brasilia,2011

Study	Exclusions criteria	Status
1	1	Excluded
2	8	Excluded
3		

Form code: C82b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords: “Building Information Modeling”Fabrication

Strings:“Building Information Modeling” AND Fabrication (All Fields: Title, Author, subject, Network, Tag)(All Fields: “Building Information Modeling” AND All Fields:Fabrication)

Studies list:

1 Oliveira, Marina Rodrigues,Modelagem virtual e prototipagem rápida aplicadas em projeto de arquitetura,Master Thesis,Universidade
2 de Sao Paulo,2011
3 Bortolini, Rafaela,Modelo para planejamento e controle logístico de obras de sistemas pré-fabricados do tipo engineer-to-order com
4 o uso de BIM 4D,Master Thesis,Universidade Federal do Rio Grande do Sul,2015

Study	Exclusions criteria	Status
1	8	Excluded
2	1	Excluded

Form code: C83b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords: BIM“Mass Customization”

Strings:BIM AND “Mass Customization” (All Fields: Title, Author, subject, Network, Tag)

(All Fields: BIMAND All Fields:”Mass Customization”)

Studies list:

1 Morais, Helen Rachel Aguiar,Complexidade e customização em massa na arquitetura contemporânea,Master Thesis,Universidade de Brasilia,2011

Study	Exclusions criteria	Status
1	1	Excluded

Form code: C84b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords: “Building Information Modeling”“Mass Customization”

Strings:“Building Information Modeling” AND “Mass Customization” (All Fields: Title, Author, subject, Network, Tag)

(All Fields: “Building Information Modeling” AND All Fields:”Mass Customization”)

Studies list:

Your search - (All Fields:"Building Information Modeling" AND All Fields:"Mass Customization") - did not match any resources.

Form code: C85b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords:BIM

“Digital Fabrication”Strings:BIM AND “Digital Fabrication” (All Fields: Title, Author, subject, Network, Tag)(All Fields: BIM AND All Fields:”Digital Fabrication”)

Studies list:

1 Oliveira, Marina Rodrigues,Modelagem virtual e prototipagem rápida aplicadas em projeto de arquitetura,Master Thesis ,Universidade de Sao Paulo,2011

2 Morais, Helen Rachel Aguiar,Complexidade e customização em massa na arquitetura contemporânea,Master Thesis, Universidade de Brasilia,2010

Study	Exclusions criteria	Status
1	1	Excluded
2	1	Excluded

Form code: C86b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords:"Building Information Modeling"“Digital Fabrication”

Strings:"Building Information Modeling" AND “Digital Fabrication” (All Fields: Title, Author, subject, Network, Tag)(All Fields: "Building Information Modeling" AND All Fields:”Digital Fabrication”)

Studies list:

1 Oliveira, Marina Rodrigues,Modelagem virtual e prototipagem rápida aplicadas em projeto de arquitetura, Master Thesis,Universidade de Sao Paulo,2011

Study	Exclusions criteria	Status
1	1	Excluded

Form code: C87b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords:"Design to Fabrication"Architecture

Strings:"Design to Fabrication" AND Architecture (All Fields: Title, Author, subject, Network, Tag)(All Fields: "Design to Fabrication" AND All Fields:Architecture)

Studies list:

1 Frantz, Arthur Pereira,Designing fault tolerant NoCs to improve reliability on SoCs,Master Thesis,Universidade Federal do Rio Grande do Sul,2007

2 Pimenta, Wallace Alane,Projeto e caracterização de um filtro gm-C sub-hertz integrado de ultra-baixo consumo,Master Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Eletrica e de Computacao,2011

Study	Exclusions criteria	Status
1	8	Excluded
2	2	Excluded

Form code: C88b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords:"Design to Fabrication"Manufactur*

Strings:"Design to Fabrication" AND Manufactur*

(All Fields: Title, Author, subject, Network, Tag)(All Fields: "Design to Fabrication" AND All Fields:Manufactur*)

Studies list:

1 Bineli, Aulus Roberto Romao,Projeto, fabricação e teste de um microrreator catalítico para produção de hidrogênio a partir da reforma a vapor do etanol – Tese Doutorado,Doctoral Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Quimica,2013

2 Teoi, Augusto Yassuo,Análise dos fatores críticos de sucesso (FCS) na implantação da metodologia dimensional management system (DMS) em indústrias do ramo metal-mecânico ,Master Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Mecanica,2016

3 Polis, Joao Eduardo,Projeto e construção de parte estrutural de

protese de mão humana com movimentos,Master Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Mecanica,2009

4 Lopes, Alberto dos Santos,PROJETO E TESTES DE UM AEROGERADOR DE PEQUENO PORTE E DE UM SISTEMA DE MEDIÃÃO DE EFICIÃNCIA MECÃNICA,Master Thesis,Universidade Federal do Ceara,2011

5 Capovilla, Carlos Eduardo,Circuitos integrados de radio-recepção para a operação de multiplexação espacial de antenas em tempo real,Doctoral Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Eletrica e de Computacao,2008

6 Goncalves, Claudio Torres,Projeto e fabricação de componentes de órteses em materiais poliméricos reforçados,Master Thesis,Universidade de Sao Paulo, Escola de Engenharia de Sao Carlos,2003

7 Silva, Esly Cesar Marinho da,Aplicação de NURBS em MMCs, com apalpador touch trigger, para escaneamento de superfícies de formas livres e geometrias complexas -Doutorado,Doctoral Thesis,Universidade Federal da Paraiba,2011

8 Canto, Rodrigo Bresciani,Projeto e fabricação de moldes para prensagem isostática utilizando tecnologias CAD/CAE e prototipagem rápida,Master Thesis,Universidade de Sao Paulo, Escola de Engenharia de Sao Carlos,2002

9 Costa, Juliano Nunes,Projeto, fabricação e teste de uma microbomba sem valvulas,Master Thesis,Universidade Estadual de Campinas, Faculdade de Engenharia Mecanica,2006

10 Simoes, Heleno Ribeiro,AVALIAÇÃO DE MATERIAIS USANDO A RADIOGRAFIA COMPUTADORIZADA (CR) EMPREGANDO UM ACELERADOR LINEAR E COBALTO - 60 COMO FONTES DE ALTAS ENERGIAS ,Master Thesis,Universiadde de Taubate,2012

11 Teves, Andre da Costa,Otimização de acelerômetros MEMS eletroestáticos de alto desempenho,Master Thesis,Universidade de Sao Paulo - Escola politecnica,2013

12 Sato, Sandra Sayuri,Simulação multifísica utilizando método dos elementos finitos auxiliando interativamente a fabricação de moduladores eletro-ópticos em substratos de Bi4Ge3O12 ,Doctoral Thesis,Universidade de Sao Paulo - Escola politecnica,2015

13 Anjos, Angelica dos,Integração de blocos RF CMOS com indutores usando tecnologia Flip Chip,Doctoral Thesis,Universidade de Sao Paulo - Escola politecnica,2012

14 Oliveira Jorge Fernando de Souza,Plásticos reforçados a base de tecidos híbridos: efeitos da anisotropia e geometria normativa na caracterização mecânica e da fratura,Doctoral Thesis,Universidade Federal do Rio Grande do Norte,2013

15 Silva, Digeorgia Natalie da ,An estimation method for gate delay variability in nanometer CMOS technology - Doctorate,Doctoral Thesis,Universidade Federal do Rio Grande do Sul, Instituto de Informatica,2010

16 CabreraRiano, Fabian Leonardo,Contribuições à otimização da eficiência na transferência de energia sem-fio para dispositivos eletrônicos

miniaturizados,Doctoral Thesis,Universidade Federal de Santa Catarina, Centro Tecnologico,2016

Study	Exclusions criteria	Status
1	8	Excluded
2	8	Excluded
3	8	Excluded
4	8	Excluded
5	8	Excluded
6	8	Excluded
7	7	Excluded
8	7	Excluded
9	8	Excluded
10	1	Excluded
11	8	Excluded
12	8	Excluded
13	8	Excluded
14	8	Excluded
15	8	Excluded
16	8	Excluded

Form code: C89b

Source: Biblioteca Digital Brasileira de Teses e Dissertações – Instituto Brasileiro de Informação em Ciência e Tecnologia: http://bdtd.ibict.br/vufind/http://bdtd.ibict.br/vufind/Search/Advanced#

Search date: 2016/Dec/01

Keywords:"Design to Fabrication"Construction

Strings:"Design to Fabrication" AND Construction (All Fields: Title, Author, subject, Network, Tag)(All Fields: "Design to Fabrication" AND All Fields: Construction)

Studies list:

1 Vettoretti, Ana Claudia,Bancos para ler e conversar : parâmetros de projeto para sistema de design generativo,Master Thesis,Universidade Federal do Rio Grande do Sul - Escola de

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Study	Exclusions criteria	Status
1		
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5	7	Excluded
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7	8	Excluded
8		
9	7	Excluded
10	7	Excluded
11	2	Excluded

Appendix G- Research Centers

Research Center	Country	Reference	Context	Benefit
Birmingham City University	UK	CHEUNG, KURUL and OTI (2016)	BIM / Mass Customization	Customization
California State University	USA	WU and ISSA (2015)	BIM	Interoperability
Cardiff University, UK	UK	REZGUI and MILES (2010)	Mass Customization	Life-cycle integration
Columbia University	USA	TAYLOR and BERNSTEIN (2016)	BIM	Productivity / Interoperability
ETH Zurich	Switzerland	GIRMSCHEID and RINAS (2012)	Mass Customization	Customization / Life-cycle integration
Gehrt Technology Asia Ltd	China	LEE and KIM (2012)	Digital Fabrication / Mass Customization	Customization
George Washington University	USA	AHN et al (2016)	BIM	Life-cycle integration
Graz University of Technology	Austria	STAVRIĆ and WILTSCHE (2012)	Digital Fabrication / Design to Fabrication	Life-cycle integration
Guy Nordenson and Associates	USA	OSWALD (2014)	Design to Fabrication	Customization
Hanyang University	Korea	AHN et al (2016)	BIM	Life-cycle integration
Hong Kong Polytechnic University	China	CAO, LI and WANG (2014)	BIM	Life-cycle integration
Istanbul Technical University	Turkey	KARAMAN and RATNAGARAN (2013)	BIM	Life-cycle integration

Massachusetts Institute of Technology	USA	DURO-ROYO, MOGAS-SOLDEVILA and OXMAN (2015)	BIM / Digital Fabrication / Design to Fabrication	Customization
Middle East Technical University	Turkey	ANIL, UNAL and KURC (2012)	BIM	Interoperability
National University of Singapore	Singapore	KHALILI and CHUA (2013)	BIM	Interoperability
Newschool of Architecture and Design	USA	FARR, PIROOZFAR and ROBINSON (2014)	BIM / Mass Customization	Customization
Ohio State University	USA	CHEN, REICHARD and BELIVEAU (2010)	BIM	Interoperability
Oxford Brookes University	UK	CHEUNG, KURUL and OTI (2016)	BIM / Mass Customization	Customization
Pennsylvania State University	USA	RAMAJI and MEMARI (2016)	BIM	Life-cycle integration
RMIT University	Australia	LEON et al (2013)	BIM / Mass Customization	Interoperability
Santa Clara University	USA	SAID (2015)	BIM	Productivity / Customization
State University of New York	USA	KARAMAN and RATNAGARAN (2013)	BIM	Life-cycle integration
Tongji University	China	CAO, LI and WANG (2014)	BIM	Life-cycle integration
Universidade de Brasilia	Brasil	MORAIS (2011)	Mass Customization / Design to Fabrication	Customization
Universidade Estadual de Campinas	Brasil	SCHNEIDER (2014)	Mass Customization	Customization
Universidade Federal de Ouro Preto	Brasil	HENRIQUES (2013)	Mass Customization	Productivity / Customization
Universidade Federal de Pernambuco	Brasil	MACHADO (2005)	Mass Customization	Productivity / Customization
University of Brighton	UK	FARR, PIROOZFAR	BIM / Mass Customization	Customization

		and ROBINSON (2014)		
University of Central Lancashire	UK	GOULDING, RAHIMIAN and WANG (2014)	BIM	Interoperability / Life-cycle integration
University of Oxford	UK	GATTAS and YOU (2016)	Digital Fabrication / Design to Fabrication	Customization
University of Queensland	Australia	GATTAS and YOU (2016)	Digital Fabrication / Design to Fabrication	Customization
University of Texas	USA	WANG and LEITE (2016)	BIM	Life-cycle integration
University Park	USA	SOLNOSKY and LUTH (2015)	BIM	Interoperability / Life-cycle integration
Virginia Polytechnic Institute and State University	USA	CHEN, REICHARD and BELIVEAU (2010)	BIM	Interoperability
Woodside Energy Ltd	Australia	HOU et al. (2015)	BIM	Productivity
Yale University	USA	TAYLOR and BERNSTEIN (2016)	BIM	Productivity / Interoperability

Appendix H Data organization for identification of class of problems

Reference	Problem	Artifact	Condition	Results
AHN et al (2016)	Challenges in reorganizing the company to take full benefits of BIM adoption.	Description of organizational structures to maximize the benefits of BIM adoption	Medium-size contractors	Organizational structure to maximize BIM inplementation throughout the project lifecycle
ANIL, UNAL and KURC (2012)	Complexities in design and detailing of reinforced concrete frames	Description of requirements for simultaneous design and detailing of reinforced concrete	Client-server based environment	Flexibility in handling detailing tasks directly in the design
BARAK Et al. (2009)	Difficulty in modeling monolithic nature structures	BIM requirements for cast-in-Place Reinforced	Requirements that deal with overlapping	A set of object schemas defining relations, meth-

		Concrete	geometries	ods and attributes needed for cast-in-place reinforced concrete
CAO, LI and WANG (2014)	How coercive, mimetic and normative pressures influence BIM adoption	Concept that Isomorphic pressures influences the extent of BIM adoption	Empirically tested with survey data collected from 92 chinese construction projects	BIM adoption is a highly socialized activity motivated by rational needs and external pressure.
CHEN, REICHARD and BELIVEAU (2010)	Complexity in interfaces in construction projects	Systematic definition of data structure and dependencies of interface information	The model is developed through an object-oriented language	An object view of interfaces and interfaces modeling techniques
CHEUNG, KURUL and OTI (2016)	weak communication between stakeholders	Description of the application of a marketing concept (Service-dominant logic) in construction business	Comparison of focus, benefits and issues between mass production and mass customization	illustrate how apply marketing strategies to enrich communication in AEC industry
CHI et al. (2015)	construction productivity issues in LNG construction plants	A model to increase productivity in liquefied natural gas plant construction	Laser scanning devices, BIM models anf GPS technology	demonstration of the feasibility of utilization of sensory devices in quality control and in handling dynamic operations
LEON et al (2013)	The gap between design and fabrication	Automatec digital design for production	Manufacturing of Hyperbolic geometries and their complex intersection	Flexible automation in the integration of CAD/CAM

DURO-ROYO, MOGAS-SOLDEVILA and OXMAN (2015)	integration of design and digital fabrication	Integrated design and digital fabrication of multi-material and complex spatial objects;	direct additive manufacturing of multi-material objects .	A continuous design-to-fabrication of objects with complex geometry and complex material
EASTMAN et al. (2010)	How software experts can anticipate issues of MVD early as construction experts develop the IDM	Method to capture detailed level information requirements at the IDM phase of specification	Architectural precast concrete MVD (Model View Definitions)	Procedures for construction experts to develop Information Delivery Manuals(IDM)
FARR, PIROOZFAR and ROBINSON (2014)	The challenge of achieving mass customization	mass customizable facades using a BIM application	Customisable façade systems.	The concepts of 'Super-System','System' and 'sub-system'
FETTERMANN (2013)	Como Desenvolver Produto orientado a customizacao em massa	Metodo para desenvolvimento de produto orientado a customizacao em massa	A reducao do tempo de set up das maquinas CNC auxilia a Customizacao em Massa	Customizacao em Massa requer produtos com curto ciclo de vida
FRUTOS (2006)	Como interagir com o cliente na configuracao de produtos em customizacao em massa.	Metodo colaborativo que oferece um conjunto de passos para facilitare a configuracao de um produto customizavel	Programacao Orientada a Objetos, Analise de decisao multiatributos e programacao linear de inteiros.	integracao entre especificacoes do cliente e limitacoes tecnicas em customizacao em massa
GATTAS and YOU (2016)	Increase feasibility of digital construction	METHOD: Design-to-fabrication process for folded sandwich structures.	Limitations: non-uniform building structures.	a design-to-fabrication process for folded sandwich (origami-inspired) structures

GIRMSCHEID and RINAS (2012)	How to deal with opportunistic behavior by players in complex systems	A design model for industrialization in construction	A cooperative approach	enables mass customization in the prefabrication industry
GOULDING, RAHIMIAN and WANG (2014)	Sharing information for geographically dispersed end users	A model for web based environment for a construction site simulation	Collaborative teams,. Web-basedsystems	Web-based platform for sharing information
HENRIQUES (2013)	projeto e producao em aco com caracteristicas artesanais	Metodo de projeto de construcoes metalicas com conceitos de customizacao em massa	Utilizacao de projetos padronizados com diferentes configuracoes de conexao	sistema estrutural modulado para edificacoes customizadas em aco
HOU et al. (2015)	The limits of 2D drawings in piping assembly	Instantiation of an Augmented reality system	Investigation performed in a lab experiment	AR applications lowered task load, task completion time and assembly erros
JEONG et al. (2009)	lack of uniformity in IFC schemas for precast concrete facades	Tests to guide the use of IFC for data exchange between BIM tools on precast concrete	Precast concrete façade with BIM tools	There is a need of IFC standardization on precast concrete information exchange
KARAMAN and RATNAGARAN (2013)	The error-prone nature of tolerance accumulation	3D parametric parametric description of highway geometry suitable for data-exchange integrity	Curved steel bridge design, detailing, fabrication and erection	Interoperability requires standardization in software data exchange
KHALILI and CHUA (2013)	Integration of standardization and prefabrication	An IFC-based model to extract geometrical and topological relationships of elements	3D CAD modeling software	minimize the total number of precast, prefabricated building elements to reduce con-

				struction total cost
KHALILI and KOLARE-VIC(2016)	The challenge of customer participation in Mass customization	A method for a customization parametric design based on constraints	designers must move from customization based on selection among standard designs	Participation of customers im design
KHANZODE, FISCHER and REED (2008)	The challenge of coordination for complex MEP projects	Measurements of real benefots of using VDCc tools for MEP coordination	The use of BIM or VDC tools at a large healthcare project	reduced labor, schedule, cost, rework, installation conflicts, RFI,. Increase prefabrication
KIM et al. (2015)	Visual-based selection of scaffolding is time consuming and error-prone	A vocabulary for computerized selection of scaffoldings	Formal language to tell a computer how to select components	Appropriate semiautomated computer selection system for seletion of scaffolding
LEE et al. (2014)	Most IFC servers based on relational databases have performance problems	Development of an IFC based on object-relational database (OR-IFC)	Improving IFC performance by simplifying mapping process of inheritance structures	Benchmark tests showed OR-IFC performance improvement over relational database IFC
LEE and KIM (2012)	The challenge of mass customization of double-curved metal panels	Stretch and bending method to fabricate mass customized double-curved metal panels	Precision and a limited budget and schedule as key requirements.	an affordable and fast technique to fabricate double-curved unique panels
LINNER and BOCK (2012)	What are the concepts related to the papanese industry	no artifact	Case study approach in the japanese cultural, economic and techno-	Description and analysis of japanese large-scale house-industry

			logical context	
LUTH (2011)	The complexity of interoperability in the fragmented discpline context of the construction industry .	Refinements to the definition of construction and design engineering	*“If the database follows a universal standard for schema and content, there is no need for interoperability – everyone operates on the same database” page 914*	A BIM model should be independent of individual software packages and graphical interfaces
MACHADO (2005)	Identificar fatores desencadeadores e habilitadores da adocao de customizacao em massa	Modelo descrevendo fatores catalizadores da implementacao de customização em massa(CM).	Analise das estrategias de CM executadas por empresas brasileiras	O contexto do mercado, as caracteristicas do produto e o processo produtivo influenciam a decisao de implantar CM
MORAIS (2011)	Fabricacao digital de um elemento de formas complexas	Viabilidade economica da fabricacao digital	O arfetato fabricado em maquina CNC e por manufatura tradicional	Fabricacao Digital em Customizacao em Massa ainda e pouco comum na arquitetura
NAWARI (2012)	The need for a common standard to enable BIM to be the legal construction model	General process map for off-site construction	The state of BIM standards and its impact on off-site construction	The success of BIM depend on the ability to capture and exchange data
NEWMAN et al. (2008)	The complexity of CNC machines interoperability	no artifact	The STEP-NC interoperability standard language for CNC machines is a	CNC interoperability will only be a reality if vendors are forced to standardize their products

			long way away	
OSWALD (2014)	Design and fabrication of complex geometry	Iterative digital fabrication of complex geometry	Geometric capabilities of glue-laminated timber (glulam)	Link between traditional and digital glulam fabrication
POIRIER, Staub-French and Forgues (2015)	The lack of literature on adoption of BIM for SMEs and specialty contractors	no artifact	Case study approach on BIM adoption	SMEs and specialty contractors can reap benefits from BIM if a clear strategy is implemented
RAMAJI and MEMARI (2016)	The challenge of changing the perceived image of modular building associated with cheap and low quality	Information model required for industrial design of multistory buildings	A product information model is required for lifecycle information management of modular buildings	Industrialization of construction and building lifecycle management through modular construction
REZGUI and MILES (2010)	Coordination and management challenges that Small and Medium Enterprises (SME) are facing	The concept of "Small and Medium sized Enterprise alliances"	Building industry relies mainly on SMEs, while global market is requiring alliances	SME alliances strengthens individual business and form virtual networked organizations, service and customer driven
ROCHA (2011, Page 186)	The fragmented body of knowledge and the shortage of prescriptive support on Mass Customization	A sequence of steps for defining a customization strategy for house-building sector	A short product life cycles creates a turbulent market, but is the ideal environment for customization.	A high rate of technological changes reduces the life cycle of products

SACKS et al. (2010)	Data exchange in design and fabrication of precast facades	Experiment aiming to test the viability of using BIM for design and fabrication of architectural precast facades	Design and fabrication using simultaneously the traditional CAD and BIM tools on the same project	Using BIM for design and fabrication of precast facades is feasible, but data exchange is incomplete and inconsistent
SCHNEIDER (2014)	The design of a product family is a difficult and challenging task	A formal approach to model the customization of product families	Product family is a key concept of mass customization	To derive members of the product family to customize a client's requirement can be a simple task
SOLNOSKY and LUTH (2015)	The lack of integration among participants in structural design in AEC	Creation of an integrated structural process model	collaboration and integration among participants	A system that covers a project from planning to construction
STAVRIĆ and WILTSCHE (2012)	The complexity of geometrical definition of 3D ornaments	Generation of customized 3D architectural ornaments from design to fabrication	Digital fabrication of 3D NURBS modeling by a robotic arm	The use of digital tools to generate 3D models
TAYLOR and BERNSTEIN (2016)	How organizations evolve internally and externally with the use of BIM	A model that describes a firm's trajectory as it gains experience using BIM tools	BIM practice evolve cumulatively in a four level trajectory	Levels of BIM uses: Visualization, Coordination, Analysis, Supply chain integration
VENUGOPAL (2011)	The need for defining MVDs in a more logical manner	A model for developing modular and reusable MVDs from IFC Product Model subschemas	Focus on precast concrete components in a building	A set of criteria to define semantic concepts within IFC to improve robustness of MVDs
WANG and LEITE (2016)	Process information is rarely documented	A method for capturing and representing	Capture and representation of dis-	enhance coordination and communica-

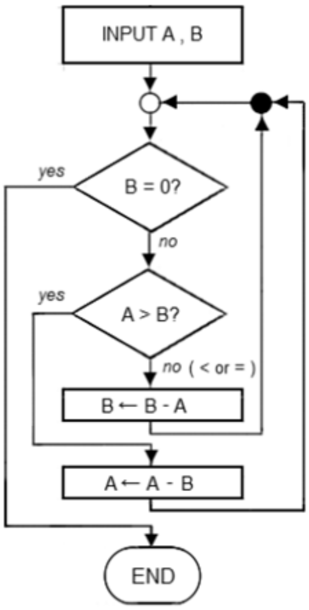
	formally	process information	cussions and decisions through direct liks to model	tion in MEP design coordination
WU and ISSA (2015)	The lack of standard processes to address BIM in green projects	Development of a BIM process model to improve green projects outcomes	The research is refined to focus on LEED projects	Improvement in the sinergy between BIM and green buildings

Appendix I Computer Programming Lectures Ministered to Designers

The workshop slides created by Zhao (2012) are very useful to master algorithms, programming, and data structure in a practical and easy way. This material enables you to understand the logic and syntax behind Visual Basic programming with the Excel interface. It is a collection of cases and tutorials. Cases are usual tasks performed with spreadsheets and tutorials contain supplemental material. The best way to learn VBA with this material is to follow along doing the same exercises in Excel, but before delving into it, read the rest of this text to get an overall concept of algorithm, programming, and data structure.

Algorithm is a finite sequence of instructions, a step-by-step procedure used for calculation, processing and reasoning. Each instruction must have a clear meaning and is written to be understood by human beings. An algorithm must be precise enough to be performed in a finite length of time. Algorithms can be expressed in many ways such as natural language, pseudocode and flow charts. Figure 1 shows the flow chart of an algorithm for calculating the greatest common divisor of two numbers *a* and *b* in using variables A and B. In order to be executed by a computer, the algorithm is transformed into a *computer program* through a *programming language,* which is a formal language that the computer understands. A *computer program* is also used to control the behavior of the computer.

Figure 1 Flow chart of an algorithm that calculates the greatest common divisor of two numbers.



The concepts of values, variables, expressions, statements, control statements, functions, types, objects, classes, and methods, are summarized in Table 1. Some variable types are available on most computers. They include the INTEGER, REAL, BOOLEAN, and CHAR. INTEGER can be positive or negative. REAL are the math Real numbers.

Table 1 Computer programming basic concepts.

	Concept	Description
Creation of simple algorithms	Value	• Piece of data which can be one of several types such as an integer, a string, a boolean (true or false)
	Variable	• It can be understood as a container that holds a value. • A variable must have a name and a good programmer chooses the name that best represents the value it holds.
	Type	• The way the computer stores the data. Can be numbers, characters, strings among others.
	Expressio n	• Combination of variables and values linked by operators such as + - * / < <= . • Expressions are the basic unit to build an algorithm.
	Statement	• Unit of code that a computer can execute. • Can be understood as a container who holds a code. • There is a special statement called "assignment" which is to assign a value or a result of the evaluation of an expression to a variable. The symbol for a assignment is :=
	Control statement	• Class of statement whose purpose is to control the flow of data through the algorithm. • The simpler is the "if" statement which executes a block of code if some condition is true or executes another block of

		code if that condition is false. • Other control statements are the ones that allow the repetition of a set of code in a cyclic loop until a certain condition fails or while a certain condition is true. • Useful to smooth the execution of actions that may vary according to the values that a variable may have. • Useful when programming a set of codes that are very similar. • Help to make the code more readable.

Smarter algorithms	Function	• Block of statements that receives inputs called arguments and have codes that act on the inputs and return values called outputs.
		• It can be understood as a block with a name.
		• As this concept is introduced, variables become more complex.
		• Now there are two groups of variables: Local and global variables.
		  o Local variables are the ones that exist only inside a function.
		  o Global variables exist also outside the function. They prevent the reuse of functions.
		• A good programmer tries to avoid as much as possible the use of global variables, because they make a program hard to be understood and debug.
		• Functions are very useful to enable code reuse.

Advanced Algorithms	Object	• Generalization of values. Combination of values into a coherent collection. • Objects have properties. A dot notation is used to reference a property. For example, if “P” is a point object, then “P.X” could be the property holding the X coordinate of this point. The point “P” could also be declared as an object with three properties, the X, Y, and Z coordinates.
	Class	• Generalization of objects. An object is an instance of a class. • As an example, in order to generalize the creation of points, a programmer could create a class called “point” with four properties called X, Y, Z, and Visible. This class can be used to declare any number of objects which would automatically inherit those four properties.
	Method	• Function specific to a certain class.
	Data structure	• An ordered collection of cells that have a name. Each cell can be accessed by the name of the list or array followed by an index that locate the cell. • Lists and Arrays are some examples. • They are useful to organize data. A Data structure comprises types (or classes) and functions (or methods) that perform coherent operations on objects of these types (or classes).

BOOLEAN is a logical variable that can have only True or False values. For example, given the Boolean variables p and q and integer variables x=5, y=8, and z=10, the two assignments p:= x = y and q:=(x ≤ y) AND (y < z) yield p = False and q = True. Boolean operations are shown on Table 2 for variables p and q. CHAR is a set of characters defined by the International Standard Organization (ISO) and American Standard Code for Information Interchange (ASCII). The ASCII set is tabulated in Table 3. It consists of 95 printable characters and 33 control characters.

Table 2 Boolean operators.

p	q	P OR q	P AND q	Not p
True	True	True	True	False
True	False	True	False	False
False	True	True	False	True
False	False	False	False	True

Data structure is a specific way of storing and organizing large amount of data efficiently. B-tree is very suited for databases, but Array is the most widely used structure and one of the most important. Array is a set of components of the same type that can be randomly accessed by the name of the array followed by a dot and an index. Arrays can be multi-dimensional. The more common are one-dimensional and two-dimensional array. One-dimensional array has each element accessed by one index. Two-dimensional array has each element accessed by two indexes. Figure 2 shows a given one-dimensional array called variable A that has four cells and indexes numbered from 0 to 3. A List is a data structure very similar to an array. Lists are distinguished from array in that lists only allow sequential access while arrays allow random access. Lists can be processed basically in two ways: FIFO and LIFO. FIFO is an acronym for First-In-First-Out and is like a queue in which the first to come is the first to be served. LIFO is an acronym for Last-In-First-Out and is like a queue in which the last to come is the first to be served. Figure is an application of LIFO. All disks must be moved from one pole to another with some rule.

1. Move one disk at a time
2. A temporary pole may be used.
3. A disk of a larger diameter may not be placed on a disk of smaller diameter.

Figure 2 Example of an array.

A.0	A.1	A.2	A.3

1.0	0.5	0.25	0.12

Algorithms depend on suitable data structures. Searching, sorting, and storing data are common tasks. Some algorithms and data structures are more efficient than others for the same task.

The book *Data Structures and Algorithms Using Visual Basic.NET* by McMillan (2005) is a very practical tutorial on how to use algorithms and data structures for implementations using VB.NET. The author presents arrays, sorting and searching algorithms as well as more advanced algorithms.

Objects, classes, methods, and Data structures are more complex concepts but very important because they are closely related to the ability to reuse functions and are very helpful for the purpose of making programs more robust and understandable. However, if not clearly understood, they may represent a trap to the programmer. Therefore, for beginners, the use of simple objects and functions are often enough to produce excellent results (WOODBURY, 2010)

Table 3 The ASCII Character Set.

	0	10	20	30	40	50	60	70
0	NUL	DLE		0	@	P	`	p
1	SOH	DC1	!	1	A	Q	a	q
2	STC	DC2	"	2	B	R	b	r
3	ETX	DC3	#	3	C	S	c	s
4	EOY	DC4	$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	HT	EM	)	9	I	Y	i	y
A	LF	SUB	*	:	J	Z	j	z
B	VT	ESC	+	;	K	[	k	{
C	FF	FS	,	<	L	\	l	|
D	CR	GS	-	=	M	]	m	}
E	SO	RS	.	>	N	^	n	~
F	SI	US	/	?	O	_	o	DEL

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Appendix J Management toward Collaboration adopted by SEMCO

ACTION	SUMMARY
Organization structure	The management structure of the company changed to a dynamic concentric structure of four layers: In the first cycle are the Counselors who coordinate the general policies and strategies. In the second level are the Partners, those that run each plant unit. In the third level are the Coordinators who comprise the crucial levels of management, such as marketing, sales, production supervisors, engineering, assembly supervisors and foremen. In the fourth level are all other employees who are called in the company as Associates.
Small Production cells	Instead of assembly lines, production machines are clustered so teams of workers can assemble a complete product, not an isolated component. This gives the workers more autonomy and responsibility. They become happier and more productive. Each worker masters several different roles.
Factory committees	Workers elect representatives that meet regularly with top managers to discuss any and all work[place issues or policies. They are empowered to audit books, question all aspects of management and even call strikes.
Job openings	An employee who meets 70 percent of the requirements is given preferential consideration over an outsider.
Job rotation	Employees exchanging roles is encouraged by the company. This can be disturbing but offers considerable advantages, such as acquiring new skills, provide employees with a broader view of the company's business, prepares more than a person for each role, and creates opportunities for those who feel trapped.
Profit sharing	The company negotiates with the workers the percentage that are distributed and they decide how to split it.
Transparency	Salaries, strategies, productivity statistics, and profit margins are made public.
Working at home	Everyone who can do it is encouraged to do so. It enhances concentration, productivity and flexibility.
Risk salary	Employees have the option of taking a percentage cut of in their salary and then receiving a compensation if the company has a good year. This program rewards those willing to take a risk and lets some of the company's labour costs with a fluctuation according its profits or losses.

Hiring process	Anyone who is about to be hired is interviewed, evaluated and approved by their collegues-to-be. Anyone who is about to be hired or promoted to a leadership position is also interviewed, evaluated and approved by those who are led by them.
Working hours	Employees are allowed to work flexible hours. This policy is linked to their commitment with the work to be done.
Unions	Unions and companies don't always agree, but there must be mutual respect and dialogue
Strikes	Strikes are respected as long as they represent what the people of that company think and feel.
Participation	Employee's involvement is the backbore of the company's management system. Every voice counts and vote.
Evaluation by subordinates	Twice a year bosses are evaluated by their subordinates. Only the respect of the led creates a real leader.
Authority	Presure over subordinates in order to make them work out of fear or any type of disrespect is not tolerated.
Job security and age	There is no promise of job security in the company, but anyone who has been in the company for more than three years or has reached the age of fifty can only be fired after a long series of approvals.
Private life	The company does not step in the employee's personal affairs. What they do when away from work as long as it does not disturb the work
Loans	The company is not considered a big family but a successful business. Occasionally, employees are helped with loans for unexpected financial problems, but not regularly for predictable expenses. Employees are not considered like children who need to be looked after, but as adults capable of making their own decision.
Satisfaction	The level of dignity of each employee must be high. He must have a sense of achievement that ensures the quality of everything that he or she does.
Vacations	Everyone must be replaceable and should take vacation days off. No excuse for accumulation vacation days.

Source: Adapted from Semler (1993)