An exploration of design systems for mass customization of factory-built timber frame homes

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ABSTRACT: Demographic trends are forcing the homebuilding industry to speed up the industrialization process through mass customization. Our survey of companies in the sector of factory-built timber frame homes shows that data processing for the prefabrication of houses and their structural components comprises many iterations which generate a bottleneck at the technical design function. Companies must generate considerable agility in their design function to deal with repeated change in orders and to coordinate multidisciplinary information, while controlling costs, delays and quality. In order to develop mass customization of factory-built timber houses, our study proposes a design system framework, taking advantage of a product platform based solution. The framework aims at integrating functional requirements and constraints in house engineering and manufacturing. Such conceptual work is an initial step towards emulating a multi-agent based method capable to provide proper coordination through proper data exchange required for the processes of the homebuilding value creation network.

1 INTRODUCTION

This paper addresses some of the technological challenges of manufacturing system for producing engineered wood systems for housing including roof trusses, floor joists and wall panels in consideration of the ongoing industrialization of the North American homebuilding industry. It focuses on manufacturing of panelized housing systems as opposed to modular houses. A trend towards panelization is developing in high volume homebuilding which means that builders are taking steps to streamline building and lower job site costs (Schuler & Adair, 2003). Non-volumetric panel systems are easier to transport than modular systems giving it more potential for large distribution and exportation.

These same authors see the increase in the prefabrication of residential buildings in the U.S., mostly as a result of an aging population and a consequent labor shortage on building sites. With prefabrication, a majority of wood frame components are manufactured in a factory and delivered to building sites for assembly.

The Science and Technology Council of Quebec (CST, 2003) reports that, contrary to what happened in Japan and Sweden, factory-built residential construction systems in Quebec (Canada) have so far been unable to exceed conventional site building methods. The complexity of the building construction process inherent to the multitude of needs that the end-product must satisfy appear to be a major hurdle to standardization in factory-built housing and to high production volumes being achieved. On the other hand, CST (2003) cites new market conditions appearing favourable to greater development of prefabricated systems. These include a need for enhanced productivity, a growing demand for warranties of quality and sustainability, skilled manpower shortages in industrialized countries, and the opening of growing export markets.

The ongoing consolidation in the housing industry of the United States, Canada's biggest export market for softwood lumber, is leading larger builders towards a more systematic approach to homebuilding. Design for rapid construction, efficiency and gains in productivity paves the way to the use of structural components.

In their study of the U.S. homebuilding markets, Poliquin *et al.* (2001) estimate that factory built roof systems (i.e. with engineering of trusses and assembly) were use in 60 to 70% of the housing starts, and flooring systems was used around 30 à 40%. Following the broad acceptance of manufactured roof and floor systems by stick (on-site) builders, prefabricated walls are gaining market share. For the U.S. markets, Robichaud and Fell (2002) estimated that prefabricated wall panels were used in 18% of the housing starts. They are predominantly used by large builders and in the northern parts of the U.S.

Such demands for factory-built components open the door to industrialization in residential construction, allowing it to benefit from improvements in terms of quality control, services and costs. Competitive advantages of industrialization can be expected through increased standardization of components, processes and information, as it may provide more efficient control tools and improved process coordination. In a number of industrial sectors, a similar combination of standardization and prefabrication have led to the adoption of new manufacturing techniques to develop and introduce new types of equipment leading to enhanced productivity and quality (Barlow *et al.*, 2003).

2 MASS CUSTOMIZATION AND VALUE CREATION NETWORKS

As will be shown, the reorganization of the home-building industry involving high-volume prefabrication is tied to the development of mass customization strategies through value creation networks. Mass customization is a strategy aimed at designing products and a manufacturing system capable of delivering on demand a broad range of products fitted to the specific needs of each client and at the same time maintaining high production efficiency.

Adoption of mass customization is based on three basic trends (Da Silveria *et al.* 2001). The first factor relates to the level of flexibility allowed by novel manufacturing and information technologies, which makes it possible to supply, with greater agility, an increased product variety at a lower production cost. The second factor is a growing demand for product variety and customization, as seen in housing by Schuler & Adair (2003). This forces producers to identify narrow market niches rather than to rely on conventional mass market segments. As a third factor, shorter product life cycles and increasing competition in a global market environment have caused the demise of various mass production industries, reinforcing the need for customer-focused production strategies.

The transition from conventional manufacturing to mass customization can be achieved in two different manners. In the first approach, used in the automobile industry, mass manufacturers customize products by involving customers towards the end of the manufacturing process. In other approaches, used by customized businesses, customers are involved upfront at the design and production stages, but reliance on modules and similar methods allows for delivery times comparable to those of mass producers (Pine, 1993). This latter approach is believed to be the model for factory-built construction.

Pine (1993) suggests five methods to achieve mass customization:

– customize services relating to standard products and services;
– develop products and services that can be customized;
– allow for customization at delivery point;
– shorten value chain response time;
– develop modular components to customize products and services.

Such generic approaches to mass customization may need to be adjusted to the actual industrial sector at study. According to Barlow *et al.* (2003), Japanese house prefabricators have adopted build-to-order techniques which involve standardization, prefabrication and management of the value chain such that houses can be provided with a high level of customization. With their approach, these prefabricators are able to meet the needs of individual buyers and specific market segments without incurring the costs of traditional customization. Figure 1, the value creation network as seen in high volume homebuilding involves specific actors providing certain activities and products. The ongoing consolidation and the reach of high volumes in some homebuilding networks in North America will probably have a substantial impact on distribution networks because the power of large builders as the main industry clients will increase, enabling them to impose their perspective (Schuler and Adair, 2003). The buying power of large builders may result in smaller margins and additional services, including engineering, prefabrication and installation of components.

> *"Large pro dealers are less likely to offer traditional uncharged services to larger builders than they are to offer them to smaller builders that offer larger gross margins. This may be because large builders do not value these services. On the other hand, large pro dealers are more likely to offer prefabrication and installation services to large builders than to small builders, either due to customer demand or due to the dealer feeling that there is more potential margin (and less competition) in offering services than in merely distributing products." (Abernathy et al., 2004)*

The movement toward consolidation in the value creation network for homebuilding in North America shows adoption of mass customization principles and may contribute to changing the rules of competitiveness towards "network against network" competition. It has yet to be determined whether these consolidated groups will develop cooperative business practices through electronic commerce like some recent alliances suggest. A major change in client-supplier relations could very well push them in that direction (Lefaix-Durand, 2003).

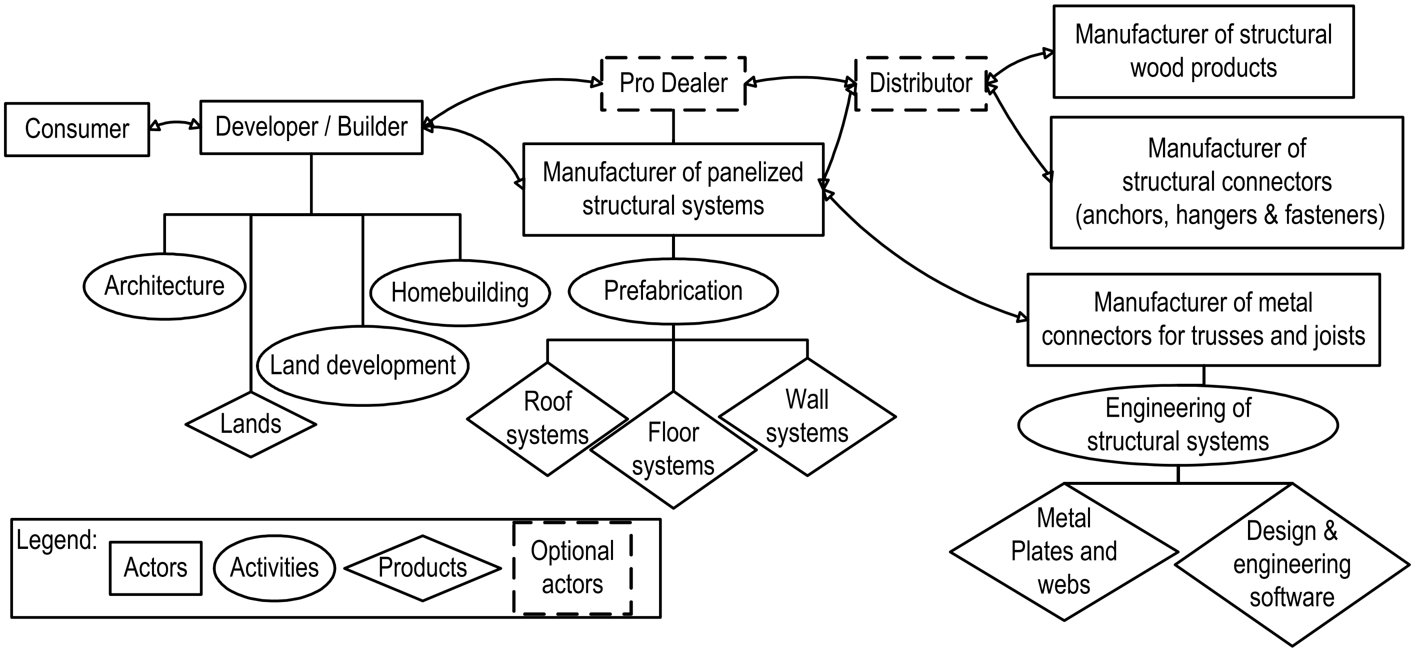

Figure 1 Prefabricated structural systems in the high volume homebuilding value creation network

"Business relations between companies are traditionally characterized by strong competition rooted in transactional issues (costs, product specifications, quality, deadline, performance, etc.). Such practices foster within value creation networks (business networks) inefficiencies in the form of accumulated stock, redundant activities, non-compliance with specifications, delays, etc."

"For more than a decade, some companies have realized that their ability to meet the needs of their clients and therefore profitability are subject to the performance of the business network as a whole (distributors, suppliers, sub-contractors, service providers, etc.) Those companies have therefore started to work differently with those partners by sharing certain information, training them, making them responsible for certain processes and trusting them." (Translated from Frayret et al., 2003).

Mass customization depends on a balance between three factors: unique features, cost and execution. In order to strike that balance for mass customization, three technical challenges were identified by Jiao and Tseng (1999): common features, product platform and integrated product development. Relating closely to the domain of engineering design, the first two challenges correspond to the development of coordination by standardization, as opposed to coordination by plans, and the third corresponds to business conducted through collaboration networks.

Considering these technical challenges, this paper proposes to analyze the current design process of 13 enterprises in the business of panelized structural systems in order to provide a coordination model necessary for its integration in a homebuilding value creation network involved in mass customization.

3 SURVEY OF TECHNOLOGIES IN THE FACTORY BUILT HOUSE INDUSTRY

Our project initiated a survey of current design practices in the prefabricated house and engineered wood systems industries, looking at the integration of design with other corporate functions in terms of software usage. Semi structured interviews were conducted in 13 companies of Central and Eastern Canada producing either modular houses, panelized houses or panelized structural systems. Products and markets varied a lot across companies, it is thus difficult to compare volumes traded. Three companies sold panelized house kits to builders (structural systems), three sold panelized house kits and three others sold modular houses to consumers (structural systems and interior design), one sold panelized wall systems and two were selling metal connectors and engineered wood products to structural systems manufacturers. All companies prefabricating structural systems relied on strong regional markets for their business development. One manufacturer of panelized house kits had nation-wide distribution as did the providers of metal connectors. The interviews aimed at identifying actual design practices in the factory-built house sector, and to determine how design functions are integrated with other company functions with respect to software utilization. The interviews were conducted with managers and technicians capable of discussing the design constraints (consultation, architecture, civil engineering, industrial engineering, equipment manufacturers, shippers, etc.) and needs related to the integration of design with other management functions in their companies and value creation network.

Results of the study are grouped under three headings: sales; design and production; and planning. The following sections describe how software programs are currently used in these three groups of functions, as well as some integration issues.

3.1 *Sales*

To sell their products to consumers, manufacturers often rely on paper or electronic catalogues, from which customers can design their houses by selecting features from the various options and components available. Two manufacturers of modular homes were using a basic architectural design software program to develop their clients' selections. Only one of them transferred this rough design into an electronic file for later use in technical design. Manufacturers of panelized housing selling to builders were reported to receive clients' orders in many different ways, from vague drawings on a piece of paper to complete architectural drawings.

Any salesperson needs to process clients' drawings into price estimates and delivery schedules. According to all manufacturers consulted, fast pricing is a major selling point. Most companies used a homemade program based on a electronic spreadsheet (e.g. MS-Excel). Two house manufacturers indicated that their pricing software was accessible on the Internet, which made it easier to circulate updates. Pricing data were updated on a weekly basis to reflect variations in material and service costs, as well as fluctuations in production capacity. Updates were provided by managers who were also responsible for generating production schedules, following up on them. They mostly entered all the data manually.

Several design and engineering software for prefabricated housing components included cost calculation modules. Only one of the panelized housing manufacturers participating in the survey used the costing module attached to their engineering software for pricing orders. The main reasons suggested for not using these costing modules included frequent wood price changes, frequent modifications to technical specifications and the excessive amount of work involved when performing too much engineering before costing. Access to databases available in design and engineering software programs is limited, as these are proprietary solutions often linked to proprietary building materials. Consequently, only suppliers are able to update data on materials. In a context of limited control over such updates, manufacturers are unable to ensure connections with other applications using materials data. This is a typical example of the problems involved in integrating the various manufacturing functions. In the factory-built housing sector, this is a frequent problem in all functions using materials data.

For complex orders, the need for validation by the engineering department during the sales process leads to repeated iterations between engineering and the client. All companies make use of electronics for internal data transfers in this situation, but many of their communications are still on paper, particularly technical drawings. Standardization of drawing symbols is minimal, and they vary with internal methods and practices. For this reason, companies prefer re-entering drawings from outside sources to ensure that all details are properly covered for production. Housing manufacturers with a large distribution network rely on various methods to simplify the integration of changes to design and submissions, and to increase their use of electronic communication.

3.2 *Design and Production*

The production of factory-built houses requires extensive manufacturing flexibility, as it involves customizing products to clients' preferences, but it does not allow for mass production unless companies achieve a high level of CAD/CAM integration. Implementation of the latter being costly, it requires significant sales. Among the roof truss manufacturers surveyed, only those producing an estimated 500 or more units a year were found to operate integrated and automated systems (including CAD/CAM). Only one of them used an automated system for walls. For all others, the housing component production system was handled manually in most aspects. As for floor joists, they are mostly manufactured on a large scale by major forest products companies, and production is usually automated. As regards floor systems, we observed a broad range of design approaches, with some companies providing a complete floor system, including engineering, while others provided only components and engineering, integration of the components being left to the house manufacturer.

Engineering software programs designed for roof trusses have reached a high level of CAD/CAM integration, from drawings to assembly. They start from architectural roof profiles and slopes, from which the structure is automatically generated, taking into account manufacturing parameters and structural design standards. Following technical validation, a cutting bill is generated; part production schedules are optimized and transferred to automated saws for cutting to precise dimensions. The parts are organized into numbered lots and moved to assembly tables, where a laser system projects the various profiles, numbers and part positions, ready for assembly. Technical validation includes consideration of the codes and standards applicable in the jurisdiction where the building is to be erected. Similar trends can be observed in the wall manufacturing sector, but to a less advanced degree.

To design their floors and roofs, all manufacturers use proprietary software from their I-joist and metal plate suppliers. CAD-generated data for the design of structural subsystems provide a link between the geometrical shapes to be built, the structural analysis and the definition of the elements required to manufacture the product. The development model of a link of this type is complex and costly. Whether owned by metal plate connector providers, automated equipment suppliers, prefabricated building manufacturers or even software developers, these programs are a strategic element of the prefabricated building manufacturing system. All manufacturers use them in isolated design units so that data used by several systems need to be re-entered. Only manufacturers using a CAD/CAM program combining a family of equipment from a single supplier are in a position of being able to implement data sharing and interoperability. Even then, such integration applies only to subsystems such as roofs, floors or walls. We failed to find a single manufacturer using proprietary solutions in such a way as to group and integrate all manufacturing units.

For these independent centers to operate, they have to be organized into repertories of multiple subsystems developed under various software environments to allow for re-utilization. All manufacturers manage these repertories and CAD-generated documents in accordance with specific procedures. Three of the manufacturers surveyed had developed a formal management system for documentation and archiving.

This same issue regarding independent automation centers was raised by Bouchard *et al.* (2002) in connection with manufacturing systems for wall panels:

> *"A study of software used in the manufacture of wall panels shows that integration with architectural drawings is very limited, even though the programs allow for various levels of integration with management and production. In addition, many software programs do not provide engineering calculations or validation against building codes. As a result, these have to be based on data included in databanks containing design values for the components."*

3.3 *Planning and Control*

Among the manufacturers participating in the survey, production management methods focused on material supply management tools (Material Requirements Planning - MRP) and Just-in-Time delivery. The planning of production processes generally uses internally developed systems based on office software, but one modular housing company was in the process of adopting a program of the Enterprise Resource Planning (ERP) type. One of the issues still requiring attention relates to the integration of production planning tools, sales tools and product design tools.

Process performance indicators vary from one company to another. Process improvements are adjusted based on in-house staff expertise, and we heard no mention of any optimization programs being applied to support process re-engineering in regards to improving production efficiency. However, manufacturers using CAD/CAM integration have access to an integrated monitoring tool for the various production functions, which they can use to track orders and work in-process in real time in addition to tracking some production indicators. We observed no bar code being used. Only one manufacturer used electronic equipment to monitor labor activities or time spent on specific projects. Quality control was typically entrusted to skilled employees and senior technicians who relied on specification sheets and the standards and building codes applicable to the area where the building was to be erected.

The survey of companies in the prefabricated wood-frame house sector showed that there is some duplication in the exchange and processing of data for prefabricated houses and structural components. There have been many advances, but the technologies used cannot effectively deal with the heavy burden placed on technical design teams. From sketches to architectural, engineering and production plans, companies have to demonstrate a great deal of agility in design in order to handle the demand for changes and at the same time control costs, timelines and quality. Sub-contracting of structural components often adds to the complexity of the design and manufacturing processes. This highly distributed environment, where information is exchanged across business functions and networks, using different data formats and linking interdisciplinary activities, poses numerous challenges in terms of coordination.

4 COORDINATION ACTIVITIES FOR STRUCTURAL SYSTEMS

Structural design involves input from various stakeholders in the value creation network. The architect of the building documents the building concept by identifying the profile of structural components, the structure permanent connections, details of the live and dead loads, and the integration of mechanical, electrical and sanitary systems. He has to design a structure that ensures that the components are not adversely affected by humidity or temperature and that the various component systems are compatible.

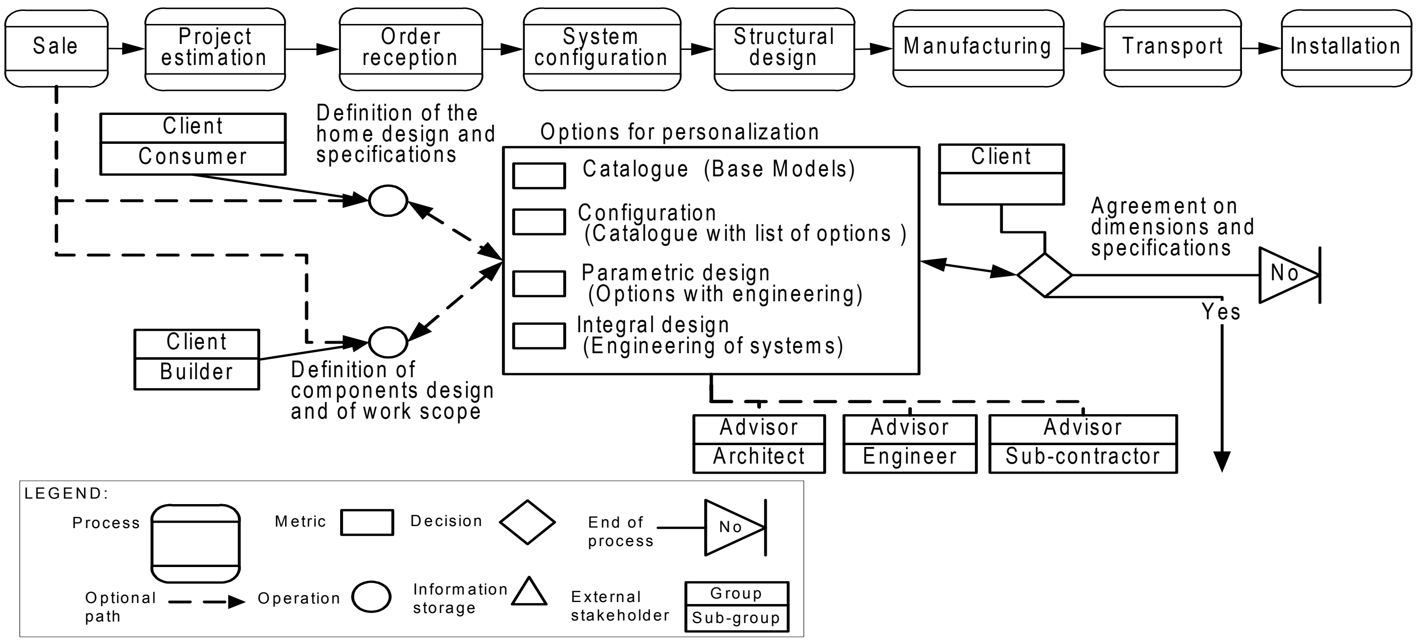

Figure 2. Description of the sale process

Once the design is set, a number of stakeholders are brought together to make the design a reality, and the activities between the players bring to light various coordination needs. Here's where a manufacturer of structural systems is integrated. As we will see, this network primarily uses plans as means of coordination, mostly relying on an intensive design process all the way up to manufacturing.

As shown in Figure 2, the sale process is organized according to the type of clients. Selling directly to the consumer is done by companies producing entire house kits, such as modular homes. It is mainly marketed through catalogues with options. The model variations offered enable changes based on client needs and choices and make it possible to accelerate certain technical validations and subsequent approvals. They also make it possible to refine the specifications submitted to manufacturer.

More frequently, sales are made to builders who want to obtain components. In this instance, they define their design as thoroughly as possible, often using an architectural plan, in order to permit integral engineering of systems

At the time of sale, information exchange becomes intensive. The buyer and the manufacturer go over the plans and review the available options. The objective is to inform the customer about quality, product availability, design options and opportunities for customization. The options and changes chosen by the customer are recorded on the model plans. The plans are reviewed by the manufacturer, who checks a general construction schedule and sends the plans, terms and conditions of sale to the design/engineering division and accounting so that they can do a technical review and costing, respectively for the selected items.

The manufacturer evaluates the difference between the model and the chosen options in terms of cost and feasibility. The project evaluations are sent to the customer so that he can go over the drawings and construction costs related to the desired changes, and if everything is satisfactory, the customer signs an agreement in principle. If more changes are requested, the construction documents are sent back to the engineering division for more revisions and then returned to the customer for approval.

Some component configuration takes place to meet specific technical requirements in addition to standard code requirements. These systems include a series of predefined options that are pre-approved and often meet private certification schemes. A manufacturer's use of these systems consists only of configuring the assembly options for the house to be produced. As presented in Figure 3, these systems are available for both building structure and envelope systems.

For structural design of systems, most work is done by computer with proprietary software under an engineer's guidance and supervision. From the systems configuration and assemblies definition, he will lay out structural elements and connect them. Cross-section properties will be analyzed and adaptations will be made to ensure integrity and stability of the structural system. For complex designs, this process requires feedback to the customer. Finally, at delivery, the manufacturer's shop drawings and assembly plans are provided in compliance with the details supplied by the builder.

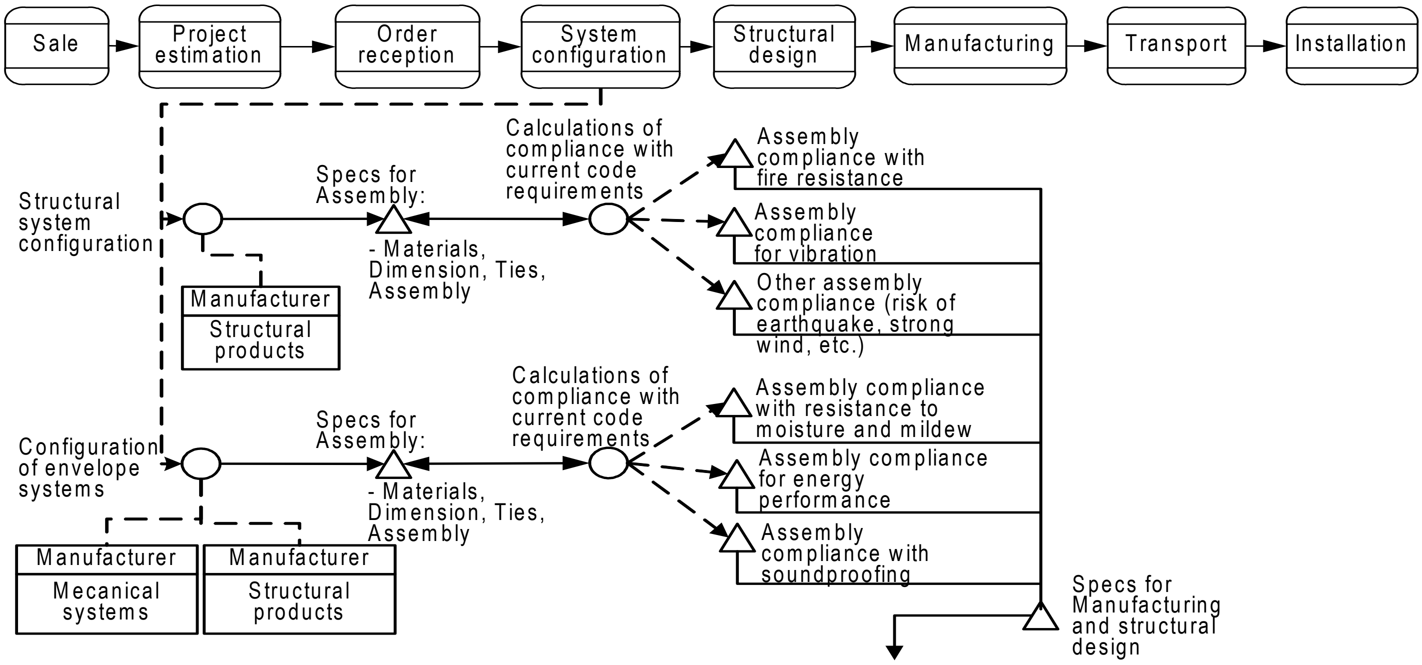

Figure 3. Description of system configuration

5 ENGINEERING DESIGN FOR MASS CUSTOMIZATION

Mass customization requires the establishment of highly integrated processes between product design and production, as the information is critical in ensuring efficient building process and delivery to the client. Faster product development for mass customization requires cooperation both within businesses and throughout the value creation network. The design processes are thus expected to play a key role in capturing, integrating, drafting and disseminating the information required by production teams.

The complexity of design tasks is a problem for mass customization, whereas many processes have to be integrated at the design level and have to be increasingly simultaneous in order to minimize costs and ensure a quick response to demand. The problems are aggravated in environments where a network of several companies has to integrate the downstream activities of planning, production and delivery with the upstream activities of response to market demand and system design. The players in a value creation network have to meet significant challenges in order to coordinate and manage information.

As seen previously, prefabrication of structural systems requires mastery of an entire series of materials, components and technical systems. From these basic steps several business models may arise, each focused on effective handling of technical and commercial constraints.

5.1 *Coordination by standardization*

Mass customization essentially lies in the ability of the product developer to identify and capture market niches and subsequently develop the technical ability to meet the needs of its different customers. Mass customization is accomplished in three ways (Jiao and Tseng, 1999): reaching the market in time, offering a variety of products and achieving economies of scale during manufacture. The first phase of a mass customization process consists in developing model homes based on trends in a market niche and ensuring compliance with the regulatory standards applicable in a particular region. Once the company's catalogue is produced, the designs are gradually modified to incorporate options and new customer trends as well as lessons learned during production to save material and labour and coordination among contributors.

5.1.1 *Common features*

Maximum repetition is essential in attaining mass production efficiency and effectiveness in sales, marketing and logistics. This is achieved by maximizing common design features so that modules, knowledge, processes, tools, equipment, etc. can be reused. Common features are often considered in relation to the physical aspects of the product or manufacturing accommodations. From a mass customization perspective, common features have to be clearly identified in relation to customers' needs or functional requirements. When customers' needs are consolidated, a set of designs can be created to establish a series of product families, which facilitates the link between customers' needs and the company's capabilities (Tseng and Jiao, 1996). This approach is reflected by repetition of structural elements seen in the catalogues of large builders of prefabricated houses; the builders use mirror designs and predetermined roofing systems to fill out their structural catalogue.

5.1.2 *Product platform*

A product platform is a breakdown of a company's catalogue that identifies common features among families of products and serves as an inventory of knowledge about various products. They are used to incorporate into designs: materials; processes; technologies; and commercial factors. They also make it possible to prevent the proliferation of products for the same customer needs.

The most visible effect of product platforms is the ability to configure variations of models quickly and inexpensively by rearranging the components within a modular design. Modular design creates a clearly defined and relatively stable technical infrastructure. The creation of new products can thus draw on a growing choice of new and improved modular components by configuring product variations. This approach should simplify sales and costing because the new product would be only a variation of known components; technical and operational evaluations would not have to be repeated in order to get an agreement in principle.

6 DISCUSSION

Reaching markets in time by linking execution time through the value creation network depends on integration of the product development process from identification of needs to delivery. From an organizational standpoint, this means expanding areas of intervention and synchronization of the product development cycle. The scope of design has to be extended to sales and service in order to take into account factors upstream and downstream of product creation. Achieving mass customization involves not only integration of the product development process, but also cohesive integration of different views over the product life cycle.

In the context of homebuilding, as in custom manufacturing industries where design is done through a network, it is difficult to optimize design activity when most of the expertise is distributed through the company and its network. Optimal design is hard to achieve because it is dependent on information exchanged between people. However, solutions to construction design problems have been developed using artificial intelligence technologies that make it possible to automate some design phases. Agent technologies might be a way to automate a great deal of design interaction. The interplay between distributed agents results in a dynamic, flexible, adapted and expandable system. Using product platforms as a basis for the collaborative design environments for prefabricated structural systems, agent technologies find valuable applications as proposed by Ugwu *et al.*(2000):

- filter information and retrieve design and project management data;
- customize information in order to be in proper line with users in distributed decision-making environments;
- automate routine design and project management tasks, including negotiation leading to the best design optimization.

This improvement in the communication of knowledge bases means that designers will be able to produce better solutions by anticipating the impact of manufacturing activities on their design decisions. This will in turn reduce changes during production and extra design work for prefabricated structural systems.

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