A COGNITIVE FRAMEWORK OF COLLABORATIVE DESIGN BETWEEN ARCHITECTS AND MANUFACTURER-DESIGNERS

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Abstract. The widespread application of prefabricated products in building has made prefabrication an indispensable part of building processes. In this context, instead of handling every detail by architects themselves, some parts of architectural design have been transferred to manufacturer-designers. This inevitably brings about problems in the integration of prefabricated products and the specific buildings they serve. As a result, collaboration between architects and manufacturer-designers takes place in building processes in various forms and extents (non-, semi-, and full-collaboration).

In this study, we aim to investigate collaborative design process from the cognitive aspect of design generation between architects and manufacturer-designers in terms of project-related products design. By applying the *Kernel of Conceptual System* theory (Tzonis et al., 1978), we intend to set up two empirical models in terms of design differences' formation in collaborative design process based on a case study with seeking the answers for the following research questions:

1. What kinds of design differences are raised in design processes?
2. Why the design differences are raised in design processes?
3. What implications could be made in developing computational models to facilitate collaborative design between architects and manufacturer-designers?

1. Background

1.1. PROBLEMS ON DIFFERENT LEVELS

Generally speaking, design involves three levels, viz. product, activity, and thinking. Therefore, we will examine the problems with regard to prefabricated products design on these three levels respectively and their relationships with each other.

1.1.1. Problems on product and activity level

Prefabrication has close relationship with building industrialization. Its developments went through the stages of launching in the late of 19th century, wide application in the first half of 20th century, and cutback in the late 1970s. Today prefabrication enters into its booming period again. It has become an indispensable part in building processes. The level of complexity and the extent of application is progressively increased in general, however may vary in different projects[1].

Due to the increasingly wide application of prefabricated products in building industry, manufacturers and their designers become progressively involved into building processes as specialist contractors and designers of construction and design teams.

Unlike architect, the title which has a clear definition, designer for prefabricated product has several different names with vague designation, such as *product architect*, *building component designer* and *industrial designer*. There are no clear requirements on education background for these designers. They may come from different disciplines such as architecture, industrial design, and engineer. However, the constraints on their designs that imposed by the nature of prefabricated products have a relatively comprehensible boundary. In this study, we use the term *manufacturer-designers* to refer to the designers under manufacturers, who design prefabricated products used in buildings.

As a result of manufacturer-designers' involvements, some parts of architectural design responsibilities actually are being transferred to them. Some scholars (Gray and Flanagan, 1989; Haviland, 1998) have presented their observations on the re-allocation of design responsibility from architects to manufacturer-designers in European and US.

The re-allocation of design responsibility leads to the fragmentation in design processes, which results in gaps between building designs of architects and product designs of manufacturer-designers. This could be reflected on product level as problems in the integration of prefabricated products and the

[1] Gibb (1999, 229) provides a tabulation in terms of variation in extent of off-site fabrication due to client, project, site and labour considerations.

specific buildings they serve in such aspects as dimension, performance, and aesthetics.

To solve the problems of integration, many kinds of open system products are developed, in which elements, components, and even systems produced by different manufacturers could be used together or be interchangeable, so as to be integrated into one building (Sarja, 1998). Some design rules such as modular coordination are also discussed to coordinate the design of architects and manufacturer-designers (Darlington, et al., 1962; Hop, 1988; Nissen, 1972; Warszawski, 1999). However, most of these methods are technique-oriented. And they concern more about the integration between products and buildings in terms of dimension and location. Other aspects of integration, such as aesthetic effects and building performance, are considered relatively limited.

Another important way of solving integration problems is to reduce the fragmentation on design activity level. Therefore collaboration between architects and manufacturer-designers is involved in design processes more or less. Most of the literatures in collaborative efforts appear to be motivated by a management-oriented approach, concentrating on the communication, information delivery, and procurement methods (Gibb 1999; Oostra, 2000).

1.1.2. Architects and manufacturer-designers

Because of different nature of building and product, constraints imposed respectively on the designs of architects and manufacturer-designers are relatively different, although they may be overlapping to some extent. As a result, architects and manufacturer-designers may have different considerations in their designs.

In addition, given the nature of their commissions, architects and manufacturer-designers look design of prefabricated products from different perspectives. Architects treat them as building components manufactured in factory, emphasizing on the building as a whole, while manufacturer-designers treat them as industrial products applied in building, concentrating on the individual components. As Osbourn (1997, 126) argued, "Manufacturers are often only concerned with the entire suitability of their particular product as it leaves the factory, and it is up to the Design Team to assess their performance relative to other criteria." [2]

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[2] Here Osbourn (1997) refers "Design Team" to architectural design team.

1.1.3. Problems on thinking level

In design processes of prefabricated products, because of different training backgrounds of architects and manufacturer-designers and different constraints imposed by building and products, design differences may be raised. People are habitually liable to ignore differences because they think differences may lead to conflicts, which represent some negative effects. However, from a positive point of view, design differences are complementary with each other in a sense and have possibilities to be integrated so as to improve the quality of buildings and products. In addition, to understand design differences well could help resolve the potential conflicts[3].

In non-collaborative design process, design differences are usually identified and resolved in a sequential way, which lead to the problems of either time-consuming processes, or poor design solutions. In collaborative design process, differences are usually identified and resolved in a parallel way through interaction between architects and manufacturer-designers. Therefore it is usually more efficient and effective comparing with non-collaborative design process.

In both non-collaborative and collaborative design processes, some potential design differences may stay unnoticed or implicit. Therefore, if we could make the potential design differences explicit, more efforts could be put into integrating these differences and resolving any possible conflicts induced. In this way, to surface design differences is significant to improve the effectivity and efficiency of both non-collaborative and collaborative design processes.

The two aspects of design process, internal mental thinking and external design activity, have close interrelations. Therefore we believe that to understand why and how design differences are raised on thinking level could help us to improve the collaboration on activity level, so as to achieve a better integration on product level.

1.2. PROJECT-RELATED PRODUCTS

According to the relationship with building projects, prefabricated products could be divided into two categories, viz. *Project-independent products* and *Project-related products* (Oostra, 2000). *Project-independent products* are standard products, which can be manufactured independently without a

[3] According to Klein and Lu (1989), "Conflict situations can be divided into two categories: *competitive* conflict situations and *cooperative* conflict situations." They argued that conflict situation in collaborative design belongs to *cooperati*ve conflict situation.

client being involved. *Project-related products* are special products, which must comply with requests from a client and develop for a specific building task.

In this study, we mainly focus on the collaborative design of *Project-related products* for the following reasons:

1. Architects are usually initiators of *Project-related products,* while manufacturer-designers are responsible for supplying such non-exist products required by architects. As a result, collaboration exists more or less in design processes.
2. It is a pragmatic way to develop new product in architecture[4] (Eekhout, 1996).
3. The mass-customization approach [5] of prefabrication leads to the tendency of more application of *Project-independent products*.
4. The development process of *Project-related products* is a relatively uncharted territory comparing with that of *Project-independent products* (Oostra 2000).

2. Research methods

This study adopts a bottom-up approach[6], intending to set up two empirical models in terms of the formation of design differences in the *project-related products* design process based on a case study.

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[4] Many scholars argued that building industry usually shuns research and experiment of new technique and products, because of the limited budget devoted to research. Eekhout (1996) proposed that one of the ways of breaking through the barrier is to conduct experiment of new building products in the specific building projects that are under architects' control. He argued "to tolerate one single experiment in each building project would also be an enormous step forward".

[5] Instead of established mass-production approach, which seeks to achieve economies of scale, today prefabrication adopts a mass-customization approach, which intends to realize the benefits of economies of scope, in order to cost-effectively fulfil the diversity requirements of clients under the help of Computer-Aid Design and Manufacture (CAD-CAM) and new manufacturing technologies (CIRIA, 1999; Evans, 1995; Gibb, 1999).

[6] According to Akin (1986), the studies of design process basically adopt two kinds of approaches. One is bottom-up approach, studying the empirical accounts of design; another is top-down approach, studying the theoretical accounts of design. For the first set of studies, they develop empirical models based on empirical study, and available theory. For the second set, they deal with the theoretical issues in the area.

A design process could be seen as a decision-making process through argumentation. Although, the internal design thinking process is basically implicit, it is believed by augmentation theorists that there are models of super-structure, by applying which to analyse design discourse, could to a certain degree make explicit the internal mental process. The *Kernel of Conceptual System*, a representation framework of design argumentation, proposed by Tzonis et al. (1978) is employed in this study. In the *Kernel of Conceptual System*, a *minimum necessary structure* is developed to represent the mental structure of the person who thinks about design. In this study, the *minimum necessary structure* is used to analyse the design discourses of our case study in order to identify the reasons behind design solutions and design differences.

3. Case study—Project-related Product Design

A project in Singapore, the Esplanade: Theatres on the bay designed by Singapore DP Architects Pte. Ltd., (DPA), is chosen for this case study because:

1. The cladding system of the project is a typical representative of project-related products.
2. The design of the cladding system involves collaboration between architects and manufacturer-designers.
3. It is a representative example of contemporary collaborative design. The design of the project was started in 1992 and the construction was completed in 2002.

3.1. GENERAL INTRODUCTION OF DESIGN AND DESIGN PROCEDURE

Esplanade: Theatres on the bay is the new performing arts centre in Singapore, which is ranked among the largest performing arts facilities in the world.[7] In phase I, which was completed in 2002, the project incorporates a concert hall and a lyric theatre with 1,800 seats each. Its unique layout is largely represented by the exterior cladding systems, which are Project-related prefabricated products.

In the final design, the two distinctive domes are comprised of 10,508 outer glass panels and 7,139 sunshades, which are reduced to 13 types of sunshades and are all prefabricated in the factory. A space-frame structure is used to support these glass panels and sunshades. According to Mr. Vikas M. Gore, an exec director of DPA who is responsible for the Esplanade

[7] http://www.dparchitects.com, accessed 15 December 2001.

project, "The geometric scheme is a square grid, like a mesh spread over a surface. The analogy I often cite is a kitchen sieve..." [8]The aluminium sunshades are mounted on this complex mesh. Each sunshade is "open or closed to varying degrees, depending on its position on the surface of the shells, to shield the interior from the hot Singapore sun, while still allowing a view of the water, the civic center, town hall and other parts of the city. The shades gradually change in shape over the surface of the shells, so that the coverage they provide changes depending upon one's viewpoint."[9]

The design of the cladding system (Design Alternative of Architects) was initiated by architects, DPA. After they finished detailed design of the cladding system, a tender was called and an alternative (Design Alternative of Manufacturer-designers) offered by manufacturer, Germany MERO GmbH & Co (MERO) [10] was chosen. However, MERO's alternative adopted another structure which is different from DPA's solution. In addition, some problems still existed in terms of integration with the whole building design and some other aspects. Therefore, architects from DPA worked together with designers from MERO to form the final solution (Design Alternative of Collaborators).

3.2. THREE SCENARIOS OF DESIGN

In the design process of the cladding system, there are three sub-processes, which could represent three scenarios in terms of collaboration between architects and manufacturer-designers (*Figure 1*). We will discuss these three scenarios respectively and present the design differences we observed.

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[8] Author's interview with Mr. Vikas M. Gore on 15 Jan 2002.

[9] http://www.eemworld.com/q299/bay.htm, accessed 15 December 2001.

[10] Both these two companies are well-known in Singapore. DPA has conducted many large-scale projects and won a lot of awards. MERO is a famous manufacturer based in Germany and has a lot of branches in the world, including Singapore. Their products, especially structural glazing products, have been adopted in several projects in Singapore.

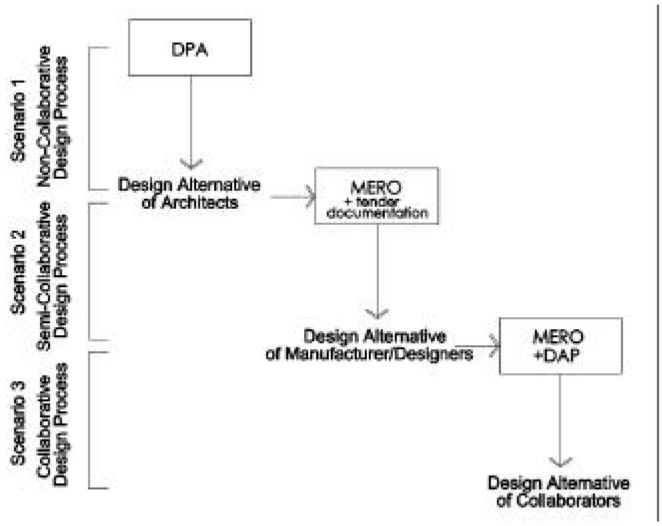

Figure 1. Three scenarios in the design process of the cladding system

3.2.1. Non-collaborative Design Scenario

In the first scenario, architects initiate the product and they work alone without any particular requirements from specific manufacturer-designers. We call it *Non-collaborative Design Scenario*.

In *Non-collaborative Design Scenario*, there are no direct design differences between these two parties. However, architects may consider some constraints from manufacturer-designers' perspective based on their own experience and knowledge available. Usually there exist some potential design differences, especially in buildability and manufacturing aspects. These potential differences will become explicit in the later stages of design or result in poor design if they remain implicitly.

3.2.2. Semi-collaborative Design Scenario

In the second scenario, manufacturer-designers design with the requirements in the tender documentation from architects. Although architects do not work together with manufacturer-designers directly, their specific requirements on the product have imposed constraints on the design of the manufacturer-designers. Therefore, we call it *Semi-collaborative Design Scenario*.

In the *Semi-collaborative Design Scenario*, design differences may be raised because manufacturer-designers work with the constraints imposed by architects but have no necessary discussion with architects. Therefore, Design Alternative of Manufacturer-designers may have several design differences comparing with Design Alternative of Architects.

Below is a distinct design difference we observed in this scenario[11].

Difference 1: structure design of the cladding system

Architects:	(In the tender documentation) using a single tube structure with steel tube up to 230 mm in diameter.
Manufacturer-designers:	Using a space frame structure, which is a three dimensional 900mm deep space truss with steel members 50 to 60 mm in diameter.

3.2.3. Collaborative Design Scenario

In the third scenario, architects and manufacturer-designers work together, however it is manufacturer-designers who initiate design proposal in this stage because of the formal contractor situation. Architects may either accept or reject the initiative proposals from manufacturer-designers or ask for more modification. In this way, they will consider and impose constraints on each other's design, and achieve an optimization together. Therefore, it is a *Collaborative Design Scenario*.

Below is a design difference on detail design we observed in this scenario.

Difference 2: Detail design of the upper node of the space frame

Manufacturer-designers:	The glazing and the sunshades should be mounted on different levels and a set of rounds are used to hold the sunshades in one fixing joint.
Architects:	The fixing design of the sunshades is too big and cumbersome. In our previous proposal, we have a much smaller and more elegant thing.
Manufacturer-designers:	We can use ball joint to make it smaller and fix it permanently, but it will be difficult to replace sunshades. Because when the ball

[11] The design differences in the design process of the Esplanade project proposed in this paper are summarized based on author's interview with Mr. Vikas M. Gore on 15 Jan 2002.

joint is loosed, all the four sunshades connected to this point will become loose.

4. Analyzing the formation of design differences on thinking level

According to the formation reason, we propose that design differences are raised in design processes as two types:

> ***Type One***: Design differences are raised because architects and manufacturer-designers have different solutions to same constraints; or
> ***Type Two***: Design differences are raised because of different constraints considered by architects and manufacturer-designers

The Design Difference 1 and 2 we observe in the section 4.2 are respectively typical representatives of Type One and Type Two design differences we proposed above. We will take them as examples to understand how the differences are formed through applying the theory of *Kernel of Conceptual System* (Tzonis et al., 1978).

*4.1.*THE THEORY OF *KERNEL OF CONCEPTUAL SYSTEM*

According to Tzonis et al. (1978), the kernel of design argumentation is made up of two braches, the deontic and the factual. *Figure 2* shows the deontic branch. The process that from a Norm (N) infers a Directive (D) is generation, and the inverse process is justification. Norm and Directive are all prescriptive statements[12]. While Fact (F) is a descriptive statement that connects the design state contained in the directive and the design state contained in the norm.

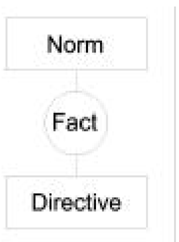

Figure 2. The deontic branch of the *Kernel of Conceptual System* (Tzonis et al., 1978)

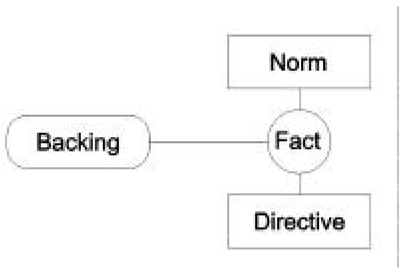

*Figure 3.*The *Kernel of Conceptual System* with Backing module (Tzonis et al., 1978)

[12] According to Tzonis et al. (1978, 4), prescriptive statements are evaluated from the point of view of validity, viz. valid or invalid, while descriptive statements are evaluated from the point of view of truth. In other words, prescriptive statements refer to what the case is, while descriptive statements refer to what it ought to be.

The factual branch of the kernel of design argumentation is comprised of two components: the Backing (B) and the Base. Backing is a descriptive statement, which describes why the fact component is true (see *Figure 3*).While Base provides arguments for the truth value of the Backing (see *Figure 4*).

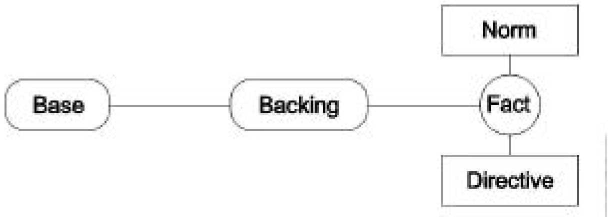

Figure 4. The *Kernel of Conceptual System* with Base module (Tzonis et al., 1978)

Below is an example:

1Norm1 (1N1):	*Provide a structure which could support the glazing and sunshades while having a curved dome shape.*
1Directive1 (1D1):	*Using a single-tube structure*
1Fact1 (1F1):	*IF using a single-tube structure, THEN it could create a curved dome, which can support the glazing and sunshades.*
1Backing1 (1B1):	*The experience of architects makes them believe that a single-tube structure is a buildable solution to support the glazing and sunshades.*
1Base1:	*The experience is trustworthy.*

4.2. TYPE ONE: DIFFERENCES RAISED BECAUSE OF DIFFERENT SOLUTIONS TO THE SAME CONSTRAINTS

The example in the last section shows how architects form one of their solutions to the structure of cladding system in the Non-collaborative Design Scenario. Below is how Manufacturer-designers in Semi-collaborative Design Scenario form their solutions in semi-collaborative scenario.

1Norm1 (1N1):	*Provide a structure which could support the glazing and sunshades while having a curved dome shape.*

1Norm2 (1N2): *The design of structure should be a solution which is familiar by MERO and suitable for MERO's production technique.*
1Directive2 (1D1): *Using a space-frame structure*
1Fact2 (1F2): *IF using a space-frame structure, THEN it could create a curve dome which can support the glazing and sunshades while being easily to be produced with the available production technique of MERO.*
1Backing2 (1B2): *MERO has a lot of experiences on designing space-frame structure.*
1Base2: *The experience is trustworthy.*

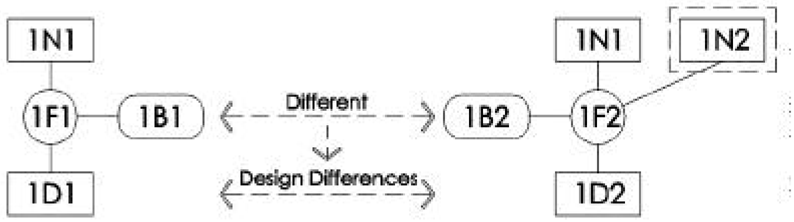

Figure 5. A diagram of Design Difference 1

We could see from *Figure 5* that the design difference is raised because architects and manufacturer-designers have different directives (1D1 and 1D2) to the same norm (1N1). It is because they have different backings, which largely depend on their pervious experiences and training backgrounds and could be reflected on their different approaches to design. However, manufacturer-designers add other norm, which also leads to their directive (1D2).

Generally speaking, every manufacturer has his favourite way of handling problems on fabrication issues. Therefore one of the motivations of MERO's proposal is building fabrication, which is suitable for their production techniques. MERO, as one of the early pioneers of using space-frame structure and using computer in their design and manufacture, has rich experience on using space frame structure.

4.3. TYPE TWO: DIFFERENCES RAISED BECAUSE OF DIFFERENT CONSTRAINTS CONSIDERED BY ARCHITECTS AND MANUFACTURER-DESIGNERS

In the detail design of the upper node of the space frame, manufacturer-designers proposed:

2Norm1 (2N1): *The joint design of the fixing of the sunshades*

	should make the sunshade could be easily replaced individually without influencing other sunshades.
2Directive1 (2D1):	*Using a set of rounds to hold the sunshades*
2Fact1 (2F1):	*IF using a set of rounds to hold the sunshades, THEN the sunshades could be easily replaced individually without influencing other sunshades.*
2Backing1(2B1):	*The experience of the manufacturer-designers tells them using separated connections for elements could make these elements be replaced individually.*
2Base1:	*The experience is trustworthy.*

Architects' opinion:

2Norm2 (2N2):	*The joint design of the fixing of the sunshades should be aesthetically elegant.*
2Directive2 (2D2):	*Using smaller ball joint.*
2Fact2 (2F2):	*IF using a smaller size joint, THEN the aesthetic effect of the sunshade joint and the overall cladding system will be better.*
2Backing2 (2B2):	*The experience of Architects tells them using smaller size joint, the aesthetic effect will be better.*
2Base2:	*The experience is trustworthy.*

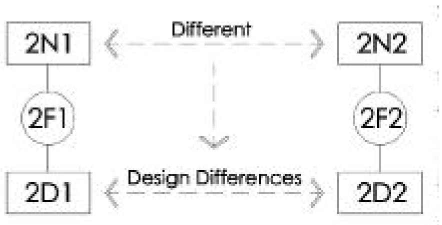

Figure 6. A diagram of Design Difference 2

As shown in *Figure 6* the directives (2D1 and 2D2) are different because of the different norms (2N1 and 2N2) considered by architects and manufacturer-designers. If using a ball joint, it could be made smaller as architects expect. But at the same time it has to be fixed permanently. Therefore it will be difficult to replace sunshades, which is concerned by manufacturer-designers. Because when a ball joint is loosed, all the four sunshades connected to this point will become loose.

5. Implications for computational framework for facilitating collaboration between architects and manufacturer-designers

Based on our analysis in section 4, we could see that making design differences explicit can help us to understand how they are raised. Therefore a computational framework which has the features of surfacing design differences will be useful to support collaboration between architects and manufacturer-designers.

Figure 7 below shows a framework for digital system and interface between architects and manufacturer-designers, which has a structure that can map the formation of the two conflict types we proposed in this paper. It can be used to facilitate the interaction between architects and manufacturer-designers on certain specific products in a parallel way in collaborative design scenario. Furthermore, it also can be used to assist the collaboration in non-collaborative and semi-collaborative design scenario by providing a database on the precedent projects, which could be sorted according to the two types of design differences.

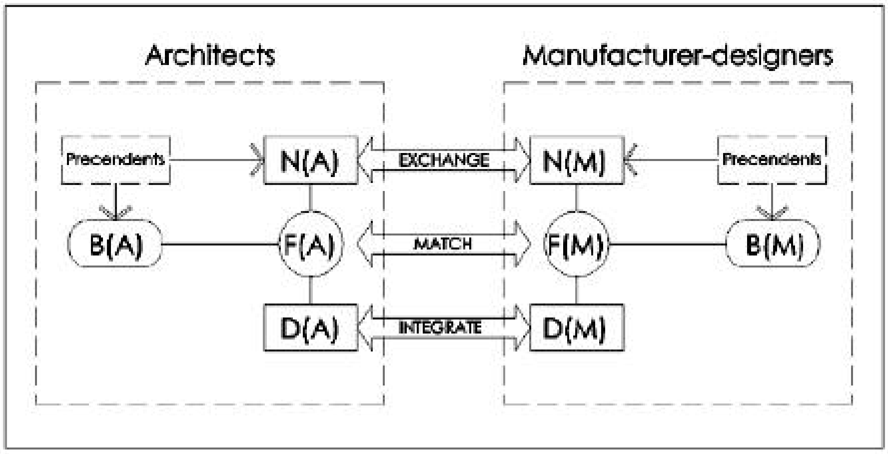

Figure 7. A framework for digital system and interface between architects and manufacturer-designers

6. Conclusion

This research has set out to develop two empirical models to examine how design differences are raised. With a case study of a project-related product in a specific building project, two types of design differences are examined and discussed, and two empirical models in terms of the formation of these design differences in semi-collaborative and collaborative design scenarios are set up. Based on the discussion, a framework for digital system and interface between architects and manufacturer-designers, which have the features on making design differences explicit, is provided. More efforts in the future will be put on constructing the computational model that could facilitate architects and manufacturer-designers to exchange their considerations on certain specific products in a parallel way.

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