COGNITIVE DIFFERENCES IN COLLABORATIVE DESIGN BETWEEN ARCHITECTURAL AND INDUSTRIAL DESIGN PROCESSES: CASE OF BUILDING PROJECT-RELATED PRODUCT DESIGN

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NATIONAL UNIVERSITY OF SINGAPORE
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Dedicated to my parents

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Summary

This study aims at establish a model of design differences in the collaborative design between architectural and industrial design processes based on a case study. To achieve this purpose, the following questions are formulated:

1. *What kinds of design differences can arise in the collaboration?*
2. *When do these design differences arise?*
3. *How do these design differences arise?*

Due to the progressive application of mass customization in manufacturing, the application of building project-related products in building industry is rapidly increasing. As a result, some stages of an architectural design process overlap with and are even substituted by an industrial design process. The collaboration between architectural and industrial design processes can range from almost none to partial, and to full-collaborations. This inevitably brings about problems with regard to the collaborative design at various levels: 1) integration of prefabricated products and specific buildings they serve at a product level, 2) fragmentation of design processes at an activity level, and 3) design differences and conflicts at a cognitive level.

In a collaborative design process some potential design differences and conflicts can remain unnoticed or implicit at a cognitive level. If they can be made explicit, more efforts can be put into integrating the design differences and resolving any possible design conflicts, and thus the design quality may be improved.

In this study, we aim to explore the collaborative design processes with a cognitive framework. Following a general comparison of design thinking between architectural and industrial design, a case study is employed to look at the structure and elements of design thinking of an actual building project. In the case study of Esplanade-Theatres on the Bay, Singapore, two types of design differences in the collaborative design processes of the project-related products, which include both system products and special products, are observed and analyzed. The *Kernel of Conceptual System* (Tzonis et al. 1978), which is a suitable theory with the key elements and structure for beliefs, judgement, and decision making, is applied to make the structure and elements of design thinking explicit for comparison. With the design reasoning processes having been mapped explicitly, the points of differences, levels of connections, and how they arise can be understood more clearly. With these findings, some understandings in terms of design differences at a cognitive level are derived for the future application of collaborative design of building project-related products.

The findings of this research are expected to shed light on the existing problems in building project-related product design with regard to the collaboration of architectural and industrial design processes. Increasing the general awareness of cognitive design differences should lead to a better understanding of collaborative design in practice. Based on the model developed in this study, further machine-based models of design difference detection can be developed to facilitate practitioners in collaborative design processes.

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Introduction

This study aims to investigate the collaboration of architectural and industrial design processes from the cognitive aspect of design differences formation. More specifically, it aims to establish a model of design differences in the collaborative design between architectural and industrial design processes based on a case study. To achieve this purpose, the following questions are formulated:

1. *What kinds of design differences can arise in the collaboration?*
2. *When do these design differences arise?*
3. *How do these design differences arise?*

According to their relationship with building projects, prefabricated products can be divided into two categories, i.e. *Project-independent products* and *Project-related products* (Oostra 2000).[1] *Project-independent products* are *standard products*, which can be manufactured independently without clients being involved; while *Project-related products* include both *special products* and *system products*, which are usually customized for specific building tasks by complying with requests from clients (Please refer to section 1.2). This study mainly focuses on the collaborative design processes of *Project-related products*.

In the design of a project-related product two design processes are involved: an *architectural design process* and an *industrial design process*. In this study the term

[1] In this study, the terms *prefabricated product*, *architectural product* and *building product* are used interchangeably.

industrial design process is used in its broad sense, which comprises the process of design and development of a product. It is assumed that an *architectural design team* refers to the one that works in a consulting firm, while an *industrial design team* in a manufacturing firm. This is usually the common setting in practice in terms of project-related product design and development in building industry. An a*rchitectural design team* and an *industrial design team* are considered as two homogenous groups, which have their own beliefs and normative systems in architectural and industrial design respectively (please refer to Chapter 2).

Brief background

The widespread application of prefabricated products in building industry has made prefabrication an indispensable part of a building process. The levels of complexity and the extent of its application are increasing despite the fact that they are varied according to different projects. With mass-customization taking over the advance from mass-production in manufacturing, more potential is being offered for the application of project-related products in building projects cost-effectively. In this context, some parts of architectural design responsibilities have been transferred to industrial design and some stages of an architectural design process overlap with and are even substituted by an industrial design process. This inevitably brings about problems at various levels: 1) integration of prefabricated products and specific buildings they serve at a product level, 2) fragmentation of design processes at an activity level, and 3) design differences and conflicts at a cognitive level (please refer to section 1.3). The collaboration between architectural and industrial design can range from almost none to partial, and to full-collaborations. It is different from the collaboration between architectural design and other design domains such as structure engineering and mechanical engineering since it involves a production-contract situation. It is also different from the collaboration between architectural design and construction as it requires more sharing of design responsibilities.

Some studies in terms of collaborative design of project-related products have emerged at the product and activity level, however few studies have been done at a thinking level, especially with regard to the design differences between architectural and industrial design. Here the term *design difference* has dual potentials. One is to be complementary to each other, while the other is to be contrary to each other. The former has the possibility to be integrated, while the latter may induce *design conflict* (please refer to section 2.2).

In the design processes of project-related products, due to the different nature of buildings and products on the one hand as well as the different requirements, patterns, and habits of architectural and industrial design practices on the other hand, design differences may arise. Normally differences tend to be avoided as they may lead to conflicts, which cause some negative effects. However, from a positive point of view, design differences are complementary to each other in a sense and have possibilities to be integrated so as to improve the quality of both architectural and industrial design. In addition, to understand design differences well can help designers to resolve the potential design conflicts in a collaborative design process.

Many scholars have discussed that design team members from different disciplines may have different views on a problem space, and it thus leads to conflicts in collaboration (Craig and Craig 2002, Donker 1999, Stempflea and Schaub 2002). Because a design problem is an ill-defined problem, a design process may include both the problem-finding and problem-solving processes, which occurs concurrently. Unlike a well-defined problem, of which the problem space can be settled at the beginning of a problem-solving process, a design problem space keeps changing during a design process. In a collaborative design process, on the one hand, the problem spaces of different design teams are dynamic and updated respectively. On the other hand, the interactions between these design teams will also help or retard the change of their respective problem spaces due to the differences in their design thinking. However, how these interactions between different design teams lead to conflicts in a collaborative design process has not been elaborated clearly and explicitly.

In a collaborative design process, some potential design differences may remain unnoticed or implicit. Therefore, if the differences in architectural and industrial design thinking can be brought to light, and if the implicit design reasoning process that takes place in a problem space can be made explicit, a better understanding towards the rise of design differences and conflicts will be achieved. Consequently, more efforts can be put into integrating the design differences and resolving any possible design conflicts. In this way, exposing design differences is paramount in improving the effectiveness and efficiency of collaborative design processes.

Problem statement

It is hypothesized that:

The design differences, which arise in the collaboration between architectural and industrial design processes, are linked with the differences in design thinking. Making these implicit differences explicit can help us better understand what, when, and how design differences arise, and thereby contributes towards a seamless transition and collaboration between these two design processes.

The fundamental assumption underlying this study is that a collaborative design process in terms of building project-related product design is important and necessary and that the current problems of collaboration are associated with the level of design thinking. There are other factors that may influence the collaborative design process and its products, such as the management issues, the social and political factors, etc. However, they are beyond the scope of this study.

Research framework

The empirical investigation of collaborative design activity is emerging as a vital element of contemporary design research. Unlike research undertaken prior to the 1990s, which "tended to focus on 'de-contextualised' activity where individuals tackled only small-scale simulations of real design problems in laboratory-like conditions", the studies currently shift their attentions to real-world collaborative design activity (Scrivener et al. 2000, 219).

According to Omer (1986), the studies of design processes 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.

This study adopts a bottom-up approach, aiming to establish a model of design difference based on a case study of an actual building project in Singapore. Following a comparative study of architectural and industrial design thinking, an existing design reasoning theory is applied to map the design reasoning processes in the case study. The findings will be analyzed and discussed to shed light on the collaborative design process in general, and in particular, on design differences in the collaboration between architectural and industrial design processes.

Cognitive framework

1. *A representation of design reasoning*

Rittel and Webber (1984, 138) stated that a design thinking process is "an argumentative process in the course of which an image of the problem and of the solution emerges gradually among the participants, as a product of incessant judgment, subjected to critical argument". From this description some common themes for the design process and design thinking which are relevant to the study can be identified. The first is that a design process is an argumentative process. The second is that it involves both reasoning by the individual designer and the discourses among participants in a design project. In this study, two sets of terms, *argumentation* and *reasoning*, *thinking* and *cognitive* are used interchangeably.

Tzonis et al. (1978, 6) argued that *design argumentation* includes two processes.[2] One is the process of generating a plan from a program. The other is the process of justifying a plan in relation to a program. 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 analyze design discourse, can to a certain degree make explicit the internal mental process.[3]

In this study, the *Kernel of Conceptual System* (Tzonis et al. 1978), which is a suitable representation of design reasoning with the key elements and structure for beliefs, judgement, and decision making, is applied to make the structure and elements of design thinking explicit for comparison.

This method was developed in the framework of a study on the transformation of architectural thinking between 1650 and 1800, the period during which the modern thinking and practices of architecture gained full ascendancy over the more archaic medieval traditions (Tzonis et al. 1978, 1). Tzonis et al. (1978) claimed that it intended to complement the architectural research approach of the time, which were derived from natural sciences and focused exclusively on observable and synchronic data of behavior.

[2] According to Toulmin et al. (1984, 14), *argumentation* is “the whole activity of making claims, challenging them, backing them up by producing reasons, criticizing those reasons, rebutting those criticisms, and so on.”

[3] According to Jeng (1995, 22), “Augmentation theory is a rigorous method to systematically analyze the representation of arguments – monologue and dialogue.”

They believed that to study design thinking historically, verbal discourses have the advantage of reliability and of spelling out more clearly the "mentality" related to architecture at a given time in history. Therefore they explored a *minimum necessary structure*, which can represent the mental structure of the person who thinks about the architecture. They claimed that this structure is "a primitive universal organization which is common to any design discourse, in engineering or in planning, in contemporary debates or in texts of antiquity, in 'common sense' conversations or in high culture discussions" (Tzonis et al. 1978, 3). By applying this structure, a sequence chain of argumentations can be mapped in correspondence with a hierarchy of norms which leads to the directives of the solutions to a project. (For detail description of the *Kernel of Conceptual System* (Tzonis et al. 1978), please refer to section 2.1)

The *Kernel of Conceptual System* (Tzonis et al. 1978) has been used successfully in different types of architectural design research in combination with case studies. In the research of precedent knowledge, Fang (1993) used it to "develop a framework for the use of architectural precedent knowledge that combines both architectural and computational perspectives". In *A Dialogical Model for Participatory Design: A Computational Approach to Group Planning,* Jeng (1995) applied the theory to study the collective reasoning processes in participatory design, which is relevant to this research though have different focuses (please refer to section 1.3.4). It was also applied in a study of cognitive bias specifically in the design of tropical architecture (Bay 2001). In this study, this theory will be used to analyze a real project in Singapore to make the implicit design reasoning processes explicit in order to understand the points of design differences, levels of connections, and how they arise.

2. Two types of design differences

In design reasoning norms and directives are prescriptive statements, which tell how the design ought to be.

> **Norms** can be seen as goals, requirements, considerations, and constraints in the design;
>
> **Directives** are instructions which generated from the norms to tell how the goals can be fulfilled;
>
> **Backings** are descriptive statements, which support certain directives can be generated from certain norms.

Based on the *Structure of Conflicts* proposed by Coombs and Avrunin (1988), which can match with the *Kernel of Conceptual System* (Tzonis et al. 1978), two types of design differences are derived according to their formation reasons:

> ***Type I Design Difference*** is a difference between the directives generated by parties who have different norms for designing the same product;
>
> ***Type II Design Difference*** is a difference between the directives generated by parties who have different backings to the same norms.

These two types of design differences will be used to understand the formation and solution of design differences that arise in the collaborative design processes of the case study. (For more discussion, please refer to Section 2.2)

3. A general comparative study between architectural and industrial design

Due to the limitations of time, cost, and mental resources, designers usually do not exhaustively search and scrutinize all the possible problem spaces. Therefore, a problem space must be narrowed to a certain reasonable size by design constraints. Thus, design constraints reflect the structures of design problems and influence the goals to be achieved by designers. In this way design constraints are related to the norms in the structure of the design reasoning theory.

To examine the different norms of architectural and industrial design, a general comparative study is conducted. It comprises two parts. Firstly, the different nature of a building and a product as well as the practice requirements of architectural and industrial design are juxtaposed and analyzed. Based on the findings, a further comparison is made between architectural and industrial design with regard to design constraints, which form the structures of architectural and industrial design problems.

Case study approach

A case study is a qualitative research method, which refers to the description and analysis of a particular entity (object, person, group, event, state, process, or whatever) and resembles deductive learning (Fang 1993, 12). It has been widely used in clinical fields such as psychology and medicine as “case history” and in sociology studies as “monographic studies” (Hamel et al. 1993, 1). Referring to a more technical definition by Yin (1984, 23),

A case study is an empirical inquiry that:

- *Investigates a contemporary phenomenon within its real-life context; when*
- *The boundaries between phenomenon and context are not clearly evident; and in which*
- *Multiple sources of evidence are used.*

Instead of aiming to achieve statistical generalization, a case study generally tries to attain analytic generalization (Yin 1984).

In a design process, a series of interrelated decisions is usually made based on a large number of considerations and factors which have interrelationship with each other in social, cultural, economic, and technical aspects. Therefore, it is difficult to discuss a design process in abstraction without reference to its context. A case study is a representation of a broader phenomenon (collaborative design between architectural and industrial design processes in this study). The processes in a same design domain are more or less homogeneous. Accordingly, through a detailed study of a case, which has rich information and context, some general conclusions and principles can be derived, which can be applied to a set of other parallel cases similar to it.

In this research, an actual project in Singapore is chosen as a case study (please refer to Chapter 3). To reduce bias in the case study, the materials of the case are gathered from multiple sources. Both firsthand materials and secondhand documents of all kinds were employed. The former include the author's interviews and correspondences with the architects, designers, and manufacturers, and the documentations of this project. The latter includes books, journals, newspapers, websites, and brochures. These full-scale materials are intended to present a three-dimensional portrait of the project instead of a prejudiced opinion from either the author or the interviewees.[4]

After the processes have been mapped explicitly and reference to the general comparison between architectural and industrial design thinking has been made, it is expected that the points of differences, the levels of connections, and the cause of these differences will be more clearly portrayed. With the new understanding, implications for improvements in collaborations and future research into the collaborative aspects of architectural and industrial design can be advanced.

Outline of the thesis

In Chapter 1 we will introduce the background and central problem of this study. Firstly, the state-of-the-art of prefabrication will be presented. The transformation from mass production to mass customization leads to the increasing application of building project-related products, the design of which is an overlapping field of architectural and industrial design. The problems associated with the collaborative design of project-related products will be examined at three levels, i.e. product, activity, and thinking. The problems of design differences at a thinking level, which is the main concern of this study, will be highlighted and some relevant studies will be reviewed.

In Chapter 2, a cognitive framework will be structured as a basis for interpreting the collaborative design process of the following case study in Chapters 3 & 4. The central

[4] As Hamel et al. (1993)'s statement makes it clear, "the variety of these materials will ensure the depth of the case study. The rigor of the definition of the object under analysis depends here on the depth of the description characteristic of the case study approach".

part of the framework is a design reasoning theory, i.e. the *Kernel of Conceptual System* (Tzonis et al. 1978), which is a suitable theory with the key elements and structure for decision making. Based on the *Kernel of Conceptual System* (Tzonis et al. 1978) and *structure of conflict* (Coombs and Avrunin, 1988), two types of design differences are derived. In addition, a comparative study of architectural and industrial design thinking is conducted.

We will proceed to Chapter 3 to present a case study of a specific project in Singapore in order to have a preliminary understanding of the design differences that arise in the collaborative design process of a project-related product. Firstly, the reasons why the project was chosen and the data sources of the case study will be explained. Secondly, a description of the project will be given and two kinds of project-related products, i.e. system products and special products, will be determined. Following that, three scenarios in terms of collaboration between architectural and industrial design processes will be identified at an activity level and the descriptions of four key design differences observed in these scenarios is tabulated at a product level.

Then in Chapter 4, by applying the cognitive framework proposed in Chapter 2, the reasoning processes of the system products and the special products will be mapped respectively in the three scenarios. Based on these mapping results, we will explain how the design differences arose in the collaboration between architectural and industrial design processes in this case study. Some possible implications that can facilitate collaborative design will be derived. Furthermore, some suggestions for future research will also be made. Following that, a conclusion will be offered to indicate the contribution and limitation of this study.

Chapter 1: Collaborative design of building project-related product under mass customization

Background, research problem statement, and literature review

In this chapter the background and the research problem of this study will be introduced in detail. Firstly the state-of-the-art of prefabrication will be presented. Then the nature of building project-related products, the design of which involves collaboration between architectural and industrial design processes, will be expounded. Following that, the problems associated with the collaborative design of project-related products will be examined at three levels, i.e. product, activity, and thinking. Some existing studies will be reviewed critically. The problem of design differences at a thinking level, which is the main concern of this study, will be highlighted and discussed.

1.1. The state-of-the-art of Prefabrication: from mass production to mass customization

Prefabricated product design is a field where architectural and industrial design overlap. In practice, both an architectural design process and an industrial design process can be involved in designing prefabricated products. The state-of-the-art of prefabrication highly influences the application of prefabricated products in the building industry and the collaboration between architectural and industrial design processes.

1.1.1. The status quo of prefabrication

Using the term *off-site fabrication* to cover both prefabrication and preassembly, Gibb (1999, 2) defined it as follows:

> *"Off-site fabrication is a process which incorporates prefabrication and preassembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site. In its fullest sense, off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation."*

From this definition it can be seen that the primary characteristic of prefabrication is that it shifts designing from an architectural design process to an industrial design process and shifts production from the construction site to the manufacturing factory[5].

Prefabrication has a close relationship with building industrialization. Its developments went through the stages of launch in the late of the 19th Century, wide application in the first half of the 20th Century, and cutback in the late 1970s. Today prefabrication enters a boom period again. It has become an indispensable part of the building processes. The level of complexity and the extent of application continue to increase in general, despite the fact that they may vary in different projects[6]. The application of customized products

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[5] The benefits of prefabrication proposed by various scholars include labor-saving, higher quality, lower price, wider choice for designers, increased predictability of project outcomes, more efficient use of materials, environmentally friendly construction methods and faster construction processes, less seasonal influence, and operative safety (Gibb 1999, Lewicki 1966, Sluzas and Ryan1977, Warszawski 1999). The new approach of moving some stages of a construction process from a outdoor construction site to indoor production facilities allows better control over some of the problems associated with construction site, such as climate, quality control, and unit costs, which are three crucial factors in construction (Sluzas and Ryan1977). However, the benefits of prefabrication listed above are only possibilities, which cannot be realized automatically without intentional actions. In addition, these benefits are mainly proposed from a construction perspective without thinking much of designing.

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

for specific building projects is rapidly increasing. Prefabrication is no longer considered temporary and monotonous.

1.1.2. From mass production to mass customization

In general, the development of prefabrication was influenced by many social, economic, and technical factors in the specific historical contexts. Figure 1 shows how in the period from 1850s to the end of the 20th Century these factors influenced prefabrication (Gibb 1999, 10). It can be observed that a number of factors that emerged in recent decades have stimulated prefabrication. Among these interrelated factors, *other sector advances, changing client expectation*, and *IT and digital controls* should be highlighted. And all the three factors lead prefabrication from mass production to mass customization.

Mass Production is defined as "the production of a large number of identical components in order to realize the benefits of economies of scale" [7] (CIRIA 1999). However, this approach may result in monotonous buildings when it achieves the economies of scale or few economies when it achieves variety in buildings (CIRIA 1999).

[7] Mass production brought about enormous increases in productivity and so as brought reductions in cost. To achieve the efficiency of production, mass production required standardization and interchangeable parts. CIRIA (1999) defines standardization as "the extensive use of components, methods or processes in which there is regularity, repetition and a background of successful practice". To some extend, standardization is considered to be the synonymy of prefabrication and mass production.

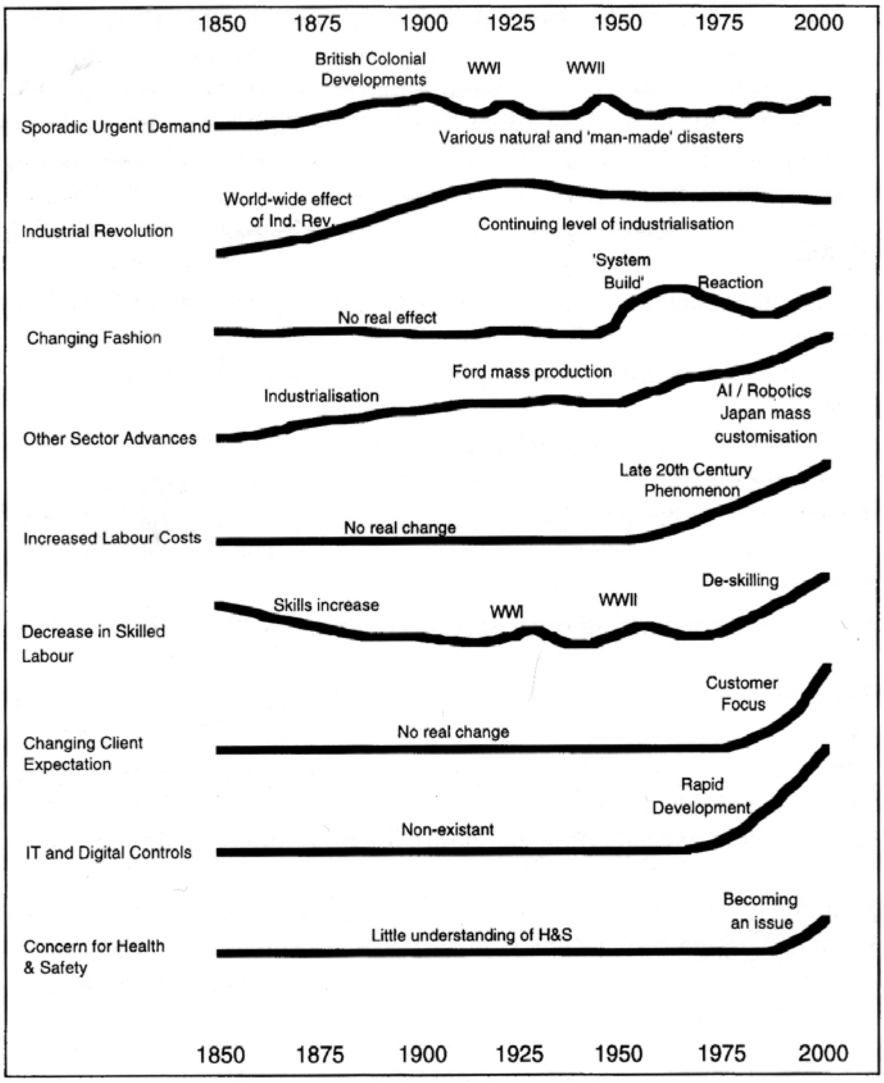

Figure 1: The historical influence of external factors on prefabrication (Gibb 1999, 10)

Customers today require diversity in products. Architects as the representatives of clients in building product markets, often intend to create uniqueness and originality in their own designs due to the nature of building as a one-off design product. On the other hand, with the help of the development of Computer Aided Design (CAD)/ Computer Aided

Manufacturing (CAM)[8], the advanced techniques of *mass customization*, which was firstly developed in Japan companies like Toyota, offered opportunities to fulfill the diverse requirements from clients most cost-effectively (Evans 1995). As a result, *mass customization*, which adopts the approach of economies of scope and requires high flexibility and variations to meet individual customer requirements, has taken over the advance from mass production in manufacturing prefabricated products (Gibb 1999).

1.2. Building project-related product

Mass customization provides more potential for design and development of customized prefabricated architectural products for specific building projects. It in turn leads to more demands for applying prefabricated products in building industry, especially *Project-related products*.

1.2.1. What is project-related product

In the spectrum of industrial design, a prefabricated architectural product lies between a customer product and an industrial product, which are at the two opposite ends. According to Oostra (2000), in terms of their relationship with building projects, prefabricated products can be divided into two categories, i.e. *project-independent products* and *project-related products*. This definition is inspired by Eekhout (1996), in which building

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[8] In the last two decades of 20th Century, with the development in computer techniques, a marriage of computer and design as well as manufacturer — Computer-Aid Design and Manufacture (CAD-CAM) — provides prefabrication new potentials. The design of products can be generated and transferred to the fabricator electronically and produced automatically by fabrication machines digitally controlled (CIRIA 1999). In this way, more complicated products can be produced cost-effectively comparing with traditional production method.

products are distinguished into three types: *special products*, *system products*, and *standard products*.

Project-independent products are *standard products*, which can be manufactured independently without a client being involved. [9] And *Project-related products* include both special products and system products. They are usually customized for specific building tasks by complying with requests from clients.

According to Eekhout (1996, 26), “special products are building products which have been completely newly designed from design to realisation for a particular project”, while *System products* are products “designed to be the lowest common denominator or the lowest common multiple between a large number of applications” (Eekhout 1996, 28). Usually, system products are developed by manufacturers and their designers, with optimising the product through using the experiences of earlier uses of the products. However, when system products are applied in a specific building project, they have to be adjusted for the actual building. In other words, a system product can be seen in the position between a special product and a standard product. Thus, the development processes of project-related products can involve two kinds of processes. One is the customization process of a system product. The other is the development process of a special product.

[9] Standard products are “usually developed entirely by producers, by industrial designers or by product architects commissioned by producers with the intention of putting these products on the market via a particular dealer network” (Eekhout 1996, 28-29). With Standard products the influence of architects is limited to “choosing the product or the various versions offered as standard” and there is usually “no more engineering, no design work for project application needs to be done” (Eekhout 1996, 28-29).

1.2.2. Why project-related product

In this study we mainly focus on the project-related products due to the following reasons:

1. *Collaboration between architectural and industrial design processes often exist in the development processes of project-related products. A Project-related product* is usually initiated by an architectural design process. Therefore, an architectural design team plays an important role in the development process. On the other hand, an industrial design process is involved to supply such a non-existent product required by an architectural design team. As a result, collaboration exists more or less in the design and development process of a project-related product. Because a project-related product is usually a one-off design for a specific building project, it involves more collaboration between architectural and industrial design processes compared with a project-independent product.

2. *It is a pragmatic way to develop new prefabricated products in architecture*. Many scholars have argued that the building industry usually shuns research and experiments on new techniques and products because of the limited budget that is devoted to research. Eekhout (1996) proposed that one of the ways of breaking through the barrier is to conduct experiments on new building products in the specific building projects that are under the control of architectural design teams. He argued that to tolerate one single experiment in each building project would also be an enormous step forward. In this way, it is important for the improvement of building industry to study the development process of project-related products.

3. *The development process of project-related products is a relatively uncharted territory compared with the development processes of standard products, although the application of project-related products is increasing (Oostra 2000).* There are still some problems associated with the development of project-related products at different design levels, especially problems related to collaborative design between architectural and industrial design processes.

1.3. Problems of collaborative design of project-related product

1.3.1. Three levels of design: product, activity, and thinking

Generally a design process involves two aspects: internal mental thinking and external design activity, which have interrelations with each other. In this study,

Design thinking process refers to an "argumentative process in the course of which an image of the problem and of the solution emerges gradually among the participants, as a product of incessant judgment, subjected to critical argument" (Rittel and Webber 1984, 138); and

Design practice process refers to the design procedure in design practice, which often comprises a logical sequence of activities that designers should follow step by step in order to fulfill their roles effectively in practice.

Compared to the internal design thinking process, design practice process usually involves a broader context and a managerial approach[10]. However, these two kinds of processes are interdependent and often carried out concurrently. Therefore, we can study design at three different levels, i.e. at a product level, at an activity level and at a thinking level (see Figure 2). The design practice process provides information to the designers as inputs. And through the internal design thinking process designers come out with some solutions as outputs after applying their learnt knowledge to solve the design problem. These two aspects of a design process interact with each other from the beginning to the end in an iterative manner. The considerations in the design thinking process will influence the design practice process, and vice versa. However, some stages of design practice process may involve more design thinking, while some stages may involve less. The extent may vary depending on different contexts; and the outcome of the interactions between design practice process and the design thinking process is the product of design, i.e. a building in architectural design and a product in industrial design.

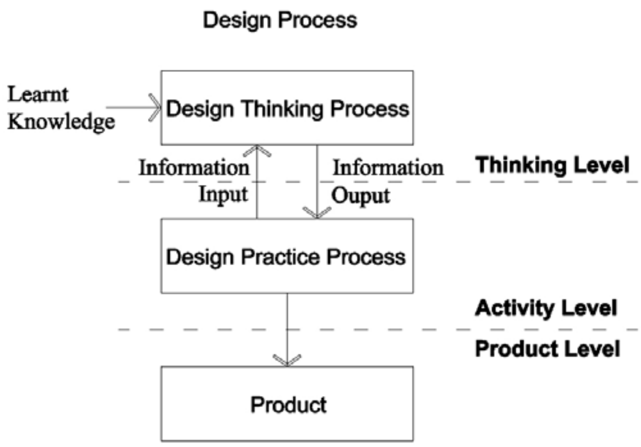

Figure 2: Three levels of design

[10] As stated by Luckman (1984, 84). "… a study of the design process on its own is not sufficient, since the majority of pressures on the designer are external to it. To understand the limitations, constraints and objectives of the design process it is necessary to know more of the research and development process of which design is a part. Within this larger process, design needs to be managed".

The phenomenon of increasing application of project-related products in building leads to the re-allocation of design responsibilities from architectural design to industrial design. As a result, collaboration between architectural and industrial design processes is involved. There are problems associated with the collaboration between these two processes at various design levels: 1) integration of prefabricated products and specific buildings they serve at a product level, 2) fragmentation of design processes at an activity level, and 3) design differences and conflicts at a cognitive level. All these problems at the three design levels are interrelated (see Figure 3) and will be examined in the following sections. Among these, the problems of design differences and conflicts on a thinking level will be highlighted.

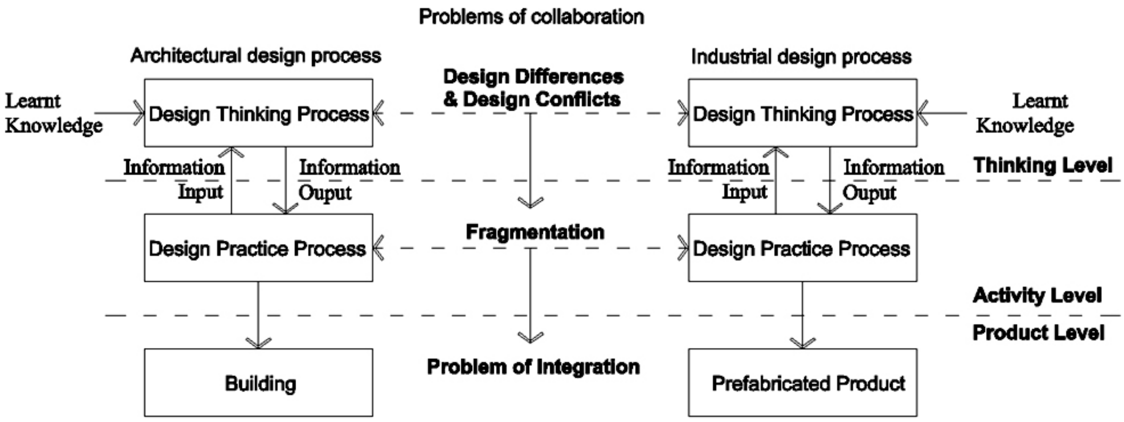

Figure 3: Problems associated with the collaborative design between architectural and industrial design processes at different design levels

1.3.2. Product level: Problems in the integration

According to Eekhout et al. (1996), the shift of an increasing number of activities in the building process from the building site to the workshop or factory, brought about needs in new industrial products for building. However, he argued, “this shift proceeded gradually from a traditional process, via rationalization of the building site process and prefabrication to flexible production and industrialization, but failed to lead sufficiently to building products interesting for architecture”. One of the important reasons that result in these unattractive building products is due to the problems associated with the integration of prefabricated products and the specific buildings they serve at a product level.

In the design of a project-related product, usually some requirements from an architectural design team will be given to an industrial design team, in the form of performance specification or product specification, which can help improve the integration of the building and the product. However, because a design problem is an ill-defined problem and has dynamic design problem space which keeps changing during the design process, just like the brief of clients in architectural design, these requirements from an architectural design team usually cannot settle the industrial design problems with complete explicitness (please refer to section 1.3.4). In addition, one building project usually adopts many architectural products produced by different manufacturers. Therefore, there are still problems associated with the integration between these architectural products and the buildings they are applied to.

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 can be used together or be interchangeable, so as to be integrated into one building (Sarja 1998). With the development of mass customization, there is no longer the necessity for “identical” standardization. “More effort is placed on the standardisation of interfaces between components which allows interchangeability and maximizes choice” (Gibb 1999, 3). Some design rules such as modular coordination are also discussed to coordinate architectural and industrial design[11] (Darlington, et al. 1962; Hop 1988; Nissen 1972; Warszawski, 1999).

However, these technique-oriented methods at a product level obviously have their limitations. Firstly, they are concerned more about the integration between products and buildings in terms of dimension, location, and building performance. Other aspects of integration, such as aesthetic effects, environmental performance, adaptability to particular site and changes over time are considered relatively limited[12]. Secondly, the integration proposed by these technical methods will not be achieved until they are applied successfully in design processes. Therefore, to answer these questions, we have to discuss them at an activity and a thinking level.

1.3.3. Activity level: Fragmentation in design processes

In building industry there are many kinds of procurement strategies, in which manufacturers are involved in architectural design and construction processes in different stages and contribute in different ways. Due to the increasingly wide application of prefabricated products in building industry, manufacturers and industrial design teams

[11] As Adler (1998, 100) proposed, ideally "Rational, industrialised building with prefabricated components presupposed co-ordination of sizes, performances and joint characteristics. Standardised rules for modular co-ordination, performance analysis and jointing of components, proved to be vital instruments in the development of the component technology. The increased range of components created, in its turn, a demand for simple and easily understood technical literature and planning guides. Experience proved that actual, systematised and open product information were crucial for the implementation of prefabricated building components and building parts. This kind of information enabled the performances of the building products to be assessed at the outset of the building process."

[12] Adler (1998, 105-106) proposed the question of "how social, ecological, political and other changing criteria can be added to a requirement pattern hitherto dominated by narrow technical and economic criteria".

become progressively involved into building processes as specialist contractors and consultants, especially in the development of project-related products[13]. As a result, some parts of architectural design responsibilities actually are transferred to industrial design[14] (AJ 1991, Gray and Flanagan1989; Haviland 1998).

The re-allocation of design responsibility leads to fragmentation in design processes where some stages of an architectural design process overlap and are even substituted by an industrial design process. It results in gaps between building and product design and is reflected at a product level as problems in the integration of prefabricated products and the specific buildings they serve. Gray (1998) argued that geographic separation, sub-contracting within the group, and time of involvement of participants involved in the project impede the transfer of ideas, design concepts, and detail designs between each group and thus deduce value creation.

In this kind of fragmented non-collaborative processes, group design usually adopts a serial approach, which may result in either time-consuming processes or poor design solutions. Therefore, to reduce the fragmentation and improve the quality of buildings, collaborations between architectural and industrial design processes are involved. A

[13] A study in UK (Gray and Flanagan 1989) summarized four main categories of sub-contracting, ranging from "fix only", such as a brickwork sub-contractor, to a full package covered design, manufacture, supply and fix, such as the specialist curtain walling sub-contractor. They claimed that many companies may offer a combination of these options depending on the specific project demands. And they also claimed that the phenomenon of shifting design responsibility from architectural design to industrial design is widespread in UK.

[14] AJ (1991, 36-37) proposed three reasons of the growth of specialist contactor design involvement. Firstly, it is due to the diverse range of technologies employed in modern industrialised buildings, some of which may fall outside normal architectural experience. Therefore, architecture design needs industrial design to deliver its design intent. Secondly, it is the result of architects' reducing workloads by handing over the task of generating the bulk of production information to manufacturers. Thirdly, architects intend to offload responsibility for the performance of the building fabric to contractors

collaborative design adopts a parallel interaction approach, which is generally more efficient and effective compared to a non-collaborative design process.

There are collaborative design studies for various building design domains. However, research of specific domain problems between architectural and industrial design is limited. In addition, the collaboration between architectural and industrial design has unique characteristics from the collaboration between architectural design and other design domains such as structural and mechanical engineering since it involves a production-contract situation. It is also different from the collaboration between architectural design and construction as it requires more sharing of design responsibilities.

Most of the literature on collaborations between architectural and industrial design processes appear to be motivated by a management-oriented approach, concentrating on the communication, information delivery, and procurement methods. Some strategies suggested by previous researchers include:

A. Letting manufacturers and industrial design teams get involved in the collaborative design process in the earlier stages. (Gray 1998, 143; AJ 1991, 36-41)
B. Improving exchange of information between architectural and industrial design processes, which should be in a bi-directional and interactive way to give designers the opportunity to integrate the more detailed description of sub-parts. (Gray 1998, 144; Troyer 1998).
C. Architectural design should leave more space for industrial design in terms of the constraints they pose, especially on the detail design and production aspects, where

different manufacturers may have their own approaches based on their techniques and experiences. (Gray 1998)

D. An architectural design team should set up a steady partnership with some industrial design teams, so as to be familiar with each other's habitual solution. (Gibb 1999, 191; Lahdenpreä 1998, 156)

Most of these strategies deal with the fragmentation of design processes merely based on managing external activities and some of them discuss it on quite a general level without a detailed exploration and explanation. In addition, most of these studies discuss the problem from construction perspective, focusing on construction and manufacturing aspects, instead of design aspect. One of the reasons behind the fragmentation, which lies in the different thinking of architectural and industrial design, is studied limitedly. Therefore, to well understand how these design activities can be improved, we should examine them at a thinking level, especially on the differences between architectural and industrial design thinking.

1.3.4. Thinking level: Design differences between architectural and industrial design

The term *collaborate* has the meaning of working or acting in conjunction with other people toward a common purpose in an intellectual endeavor.[15] In this way, a collaborative design process should be a process in which participants work in conjunction and contribute their knowledge and beliefs to achieve a common goal. Therefore, the

[15] "Collaborate," *Merriam-Webster Online*, <http://www.m-w.com/cgi-bin/dictionary?book=Dictionary&va=collaborate> (22 June 2002).

heterogeneous knowledge and beliefs of participants, an architectural design team and an industrial design team in this study, are actually very important to their collaboration.

Many scholars have discussed that design team members from different disciplines may have different views on the problem space, and it thus leads to conflicts in collaboration (Craig and Craig 2002, Donker 1999, Stempflea and Schaub 2002). The concept of Problem Space, where reasoning takes place, refers to the way that the problem is represented (Benjafield 1997, 301). Therefore, to understand the representation of architectural and industrial design problems will help us to identify the reasons behind design differences and design conflicts and help participants, i.e. an architectural design team and an industrial design team in this study, to understand each other better.

Craig and Craig (2002) argued that it is typically in design that new issues are opened up with moves within a problem space and may lead to the transformation of the problem space itself. They proposed that collaborative interaction in design “can potentially be both a hindrance and an aid to search for suitable design solutions”. On the one hand, different designers may have different problem space representations, which are potentially overly constrained by prior knowledge. This kind of non-overlapping views of the problem spaces may lead to conflicts in collaborative design. On the other hand, by providing comments that help others discover new ways of looking at the existing issues, and by contributing new analogs and exemplars that point the way to new problem space representations, collaborators may aid the design process. Craig and Craig (2002) concluded that “an important task in supporting collaboration when interests and expertise are divided among participants is helping people modify their problem space representations in a collaborative fashion as conflicts between issues arise". However, they did not explain in detail how the differences of problem spaces lead to the conflicts in collaborative design.

A design process is a problem-finding and problem-solving process. Unlike those well-defined problems, the problem space of which can be settled at the beginning of the process, design problems are ill-defined and their problem spaces keep changing during the design processes. [16] In the collaborative design process, on the one hand, the problem spaces of different disciplines always transform respectively. On the other hand, the interactions between different disciplines will also help or retard the change of the problem spaces of each other because of their differences in design thinking. Therefore, in a collaborative design process the problem space of a project is often updated and dynamic when participants interact with each other (Donker 1999, 40). As a result, the differences cannot be identified explicitly and completely at the beginning of the process. In collaborative design the interactions between two parties can change the problem space of each other through reflection-in-action, and it is a continuous and an iterative

[16] Rittel and Webber (1984) elaborated ten notable properties of wicked problem, they are:

1. *There is no definitive formulation of a wicked problem*
2. *Wicked problems have no stopping rule*
3. *Solutions to wicked problems are not true-or-false, but good-or-bad*
4. *There is no immediate and no ultimate test of a solution to a wicked problem*
5. *Every solution to a wicked problem is a 'one-shot operation'; because there is no opportunity to learn by trial-and-error, every attempt counts significantly*
6. *Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan*
7. *Every wicked problem is essentially unique*
8. *Every wicked problem can be considered to be a symptom of another problem*
9. *The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.*
10. *The planner has no right to be wrong*

interactive process (Schön 1983). Architectural and industrial design teams define and redefine their problem spaces through arguing with each other and within their teams in the collaborative design processes. Thus, to understand how design differences arise, what the differences of architectural and industrial design thinking are needs to be identified and the design reasoning processes in the collaborative design process needs to be made explicit.

Due to the different nature of buildings and products and different requirements of practices, the ways of thinking in architectural and industrial design are relatively different, although they may be overlapping to some extent. Given the nature of their commissions, architectural design and industrial design view design of prefabricated products from different perspectives. Architectural design treats them as building components manufactured in a factory, emphasizing the building as a whole, while industrial design treats them as industrial products applied in building, concentrating on the individual components. [17] As a result, these different considerations may lead to design differences in the collaboration between architectural and industrial design processes (please refer to Chapter 2).

Normally differences tend to be avoided as they may lead to conflicts, which cause some negative effects. However, from a positive point of view, design differences are complementary to each other in a sense and have possibilities to be integrated so as to

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

improve the quality of both architecture and products. In addition, to understand design differences well can help designers to resolve the potential conflicts.

In a collaborative design process, some potential design differences and conflicts may remain unnoticed or implicit. Sometimes they may be unnoticed at the design stage until the building or the product is actually built and used. Therefore, if we can make the potential design differences explicit, more efforts can be put into integrating these differences and resolving any possible conflicts induced. In this way, exposing design differences is significant to improve the effectiveness and efficiency of collaborative design processes.

Since the two aspects of design processes, i.e. internal mental thinking and external design activity have close interrelations, we believe that to understand how design differences arise at a thinking level can help us to improve the collaboration at an activity level so as to achieve a better integration at a product level.

A large body of work is devoted to conflict study in artificial intelligence and social sciences. However, in the design field, design conflict detection and resolution study has only been lightly explored, and most of those focus on conflict resolution with ambiguous and implicit explanation of conflict formation and detection, such as in the studies by Craig and Craig (2002) as well as Stempflea and Schaub (2002). In addition, design conflict detection is usually studied in a general manner, without a detailed exploration in domain-specific knowledge, such as in the study by Klein (1992).

A comparatively well considered field in terms of design conflict study is participatory design, the study by Jeng (1995) for instance. However, there are some fundamental differences between participatory design and the collaborative design in this study. First of all, the participants involved in a participatory design are not only experts but also the general public and thus the psychological factors are more important than factors associated with design. Secondly, in participatory design, collective design generation usually occurs at the very early stage of the design process, while in collaborative design in this study it is crucial in the whole design process.

This study aims at setting up a model of design differences in the collaborative design between architectural and industrial design processes based on a case study. To achieve this purpose, the following questions are formulated:

1. *What kinds of design differences can arise in the collaboration?*
2. *When do these design differences arise?*
3. *How do these design differences arise?*

1.4. Summary

This chapter has set out to answer the questions of why and what we will study in this research. Prefabrication as an effective and efficient way of dealing with design and construction problems in building industry is regaining its popularity. With developments in CAD/CAM and manufacturing technology, mass customization is taking over the advance of mass production in manufacturing. It provides enormous potential for the application from project-related products in building industry cost effectively. Project-related products refer to both special products tailor-made and system products customized for specific building projects. As a result, some parts of an architectural design process overlap with and are even substituted by an industrial design process and the collaboration between these two processes is involved. Compared with the development process of a project-independent product, that of a project-related product involves more collaboration between architectural and industrial design. In addition, the research of the latter is a relatively uncharted territory. The newly emerging trend inevitably brings about problems associated with collaboration between architectural and industrial design processes at various design levels: 1) integration of prefabricated products and specific buildings they serve at a product level, 2) fragmentation of design processes at an activity level, and 3) design differences and conflicts at a cognitive level. There are collaborative design studies at a product and an activity level, but relatively little at a cognitive level. There are also collaborative design studies of various building consultants, but not specifically on the domain problems between architectural and industrial design. Therefore, among these interrelated problems, the last one, which focuses on how design differences arise at a cognitive level, is the primary concern of this study. Given the close interrelated connections among these levels, it is positive that to answer the questions at a thinking level will help improve the collaboration at an activity level, which will, in turn, achieve a better integration at a product level.

Chapter 2: Differences in architectural and industrial design thinking

A cognitive framework to explore design difference in collaborative design thinking

In the previous chapter, it was introduced that the design of building project-related products, as an overlapping field of architectural and industrial design, involves problems associated with collaboration at various levels. The problems of design differences at a cognitive level were highlighted and discussed. With these understandings, in this chapter a cognitive framework will be proposed as a theoretical base for further understanding the collaborative process exemplified in a selected case study in Chapter 3 and Chapter 4. The case chosen is Esplanade-Theatres on the Bay project in Singapore. The roof cladding system of this project embraces both system products and special products and the design of it involves collaboration between an architectural and an industrial design process. The cognitive framework explored in this chapter will provide a way to explore collaborative design between these two design processes explicitly in order to see how design differences arise in their collaboration.

2.1. A representation of design reasoning

Although different designers have different beliefs, which influence their rules for design thinking and decision making, it is believed that basically there exist meta-structures of design thinking that can be shared by different designers. The *Kernel of Conceptual System* (Tzonis et al. 1978) is a suitable representation of design reasoning with the key elements and structure for beliefs, judgement, and decision making.

According to Tzonis et al. (1978), the kernel of design argumentation is made up of two branches, the deontic and the factual. Figure 4 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, which refer to what the case ought to be. Fact (F) is a descriptive statement that refers to what the case is. It connects the design state contained in the directive and the design state contained in the norm.[18]

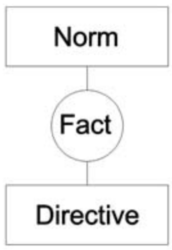

Figure 4: The deontic branch of the *Kernel of Conceptual System* (Tzonis et al. 1978, 6)

A Norm can be a goal, a need, or an objective. There is a hierarchy in norms, which means a “higher” norm warrants the “lower” norm. And a Fact is involved, which states that if the state of the lower norm is materialized, then the state of the higher norm is brought about. These norms at different levels constitute a normative system. Therefore, Deontic argumentation kernels can be combined in sequences in such a way that a directive is the “higher” norm of another directive (see Figure 5).

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

[18] According to Tzonis et al. (1978, 4), prescriptive statements are evaluated from the point of view of validity, i.e. valid or invalid, while descriptive statements are evaluated from the point of view of truth.

fact component is true (see Figure 6). Base provides arguments for the truth value of the Backing (see Figure 7).

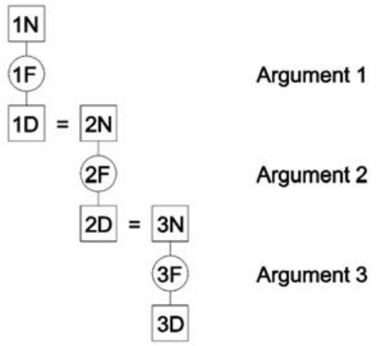

Figure 5: A linear sequence of arguments (Tzonis et al. 1978, 7)

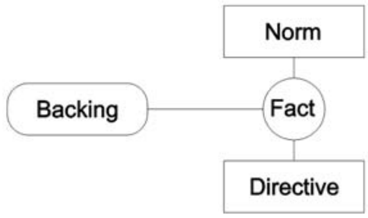

Figure 6: The *Kernel of Conceptual System* with Backing module (Tzonis et al. 1978, 9)

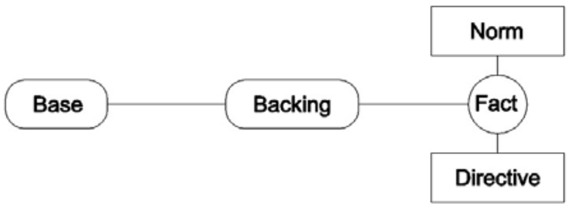

Figure 7: The *Kernel of Conceptual System* with Base module (Tzonis et al. 1978, 9)

Below is an example:

Norm (N): *Providing people the magnificent views of the Civic District around the site.*

Directive (D): *Using a glazing system for external envelop.*

Fact (F): *IF using a glazing system for external envelop, THEN the blocking of people's view can be reduced to minimum compared with other external envelop system.*

Backing (B): *The experience of the architect tells him that the visible light transmittance of glass is the highest among all kinds of building* *materials.*

Base: *The experience is trustworthy.*

2.2. Design difference in collaboration

2.2.1. Defining design difference and design conflict

According to the *Oxford English dictionary,* the definitions of difference and conflict are:

Difference: The condition, quality, or fact of being different, or not the same in quality or in essence; dissimilarity, distinction, diversity; the relation of non-agreement or non-identity between two or more things, disagreement. [19]

Conflict: The clashing or variance of opposed principles, statements, arguments, etc.[20]

From these definitions it can be seen that the *difference* emphasizes "not same" while *conflict* focuses on "opposition". Therefore, as has been discussed in section 1.3.4., *design difference* has dual potential tendencies: one is complementary to each other, while the other is contrary to each other. The former has the possibility to be integrated, while the latter may induce *design conflicts*. Although design conflicts also can be resolved to gain a mutual benefit for all participants, it is usually a compromised solution rather than an optimized solution.

[19] "Difference," *Oxford English Dictionary*, <http://80-dictionary.oed.com.libproxy1.nus.edu.sg/cgi/findword?query_type=word&queryword=difference> (22 June 2002).

[20] "Conflict," *Oxford English Dictionary*, <http://80-dictionary.oed.com.libproxy1.nus.edu.sg/cgi/findword?query_type=word&queryword=conflict> (22 June 2002).

2.2.2. Two types of design differences in collaboration

According to Coombs and Avrunin (1988)'s *structure of conflict*, three types of conflict can be identified:

> *Type I* conflict is a conflict within an individual who is moved by inconsistent considerations.
>
> *Type II* conflict is a conflict between individuals who want different things but must settle for the same thing, (e.g., a couple is planning to go on a trip together and they want to go to different places).
>
> *Type III* conflict is a conflict between individuals who want the same thing but must settle for different things, (e.g., a couple is fighting about the custody of their children).

It is can be seen that *Type I* conflict is a conflict within an individual, while both *Type II* and *Type III* conflict are conflicts between at least two parties. Because this research aims to explore the design differences that arise between two parties, Type *I* conflict will not be considered here.

Type II and *Type III* conflict can match respectively with the deontic and the factual branch of the *Kernel of Conceptual System* (Tzonis et al. 1978). Accordingly, two types of design differences can be derived in the framework of the design argumentation theory according to their formation reasons:

> ***Type I Design Difference*** is a difference between the directives generated by parties who have different norms for designing the same product;
>
> ***Type II Design Difference*** is a difference between the directives generated by parties who have different backings to the same norms.

2.2.2.1. Type I Design Difference

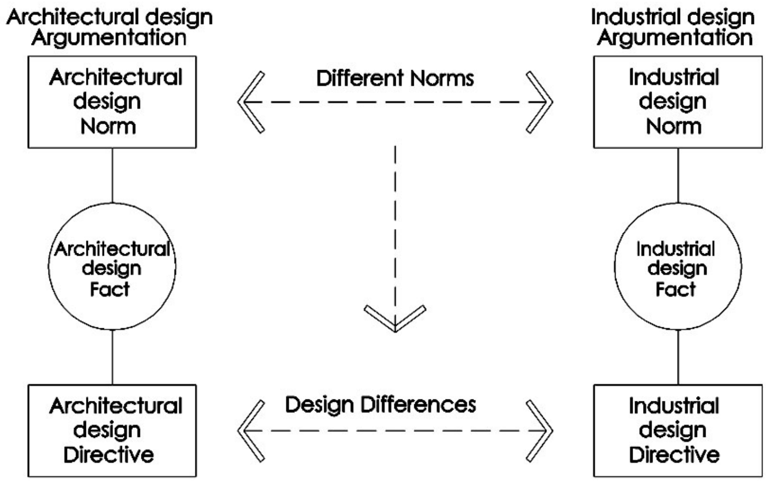

Figure 8: A diagram of Type I Design Difference formation

As shown in Figure 8 the directives (A-D and I-D) are different due to the different norms (A-N and 1-N) considered by architectural and industrial design respectively.

There are two conditions in the solution of Type I Design Difference. In the first condition, A-N and I-N are mutually exclusive, thus the design difference can lead a design conflict. To solve the design conflict, it has to decide which norm is more important. Because norms are held by different parties, to decide whose goal is more important, or less important, may involve social-psychological factors (Jeng 1995). While in the design process of building project-related product, since an architectural design team represents the client of the project, norms from its perspective often have to be well considered and complied with by an industrial design team. In design practice, to solve this kind of conflict, "an acceptable compromise rather than an optimal solution can be found through negotiation", which is a common technique in solving this kind of conflict (Jeng 1995). In the second condition, A-N and I-N are not mutually exclusive, thus they have the possibility to be integrated to achieve an optimized solution.

2.2.2.2. Type II Design Difference

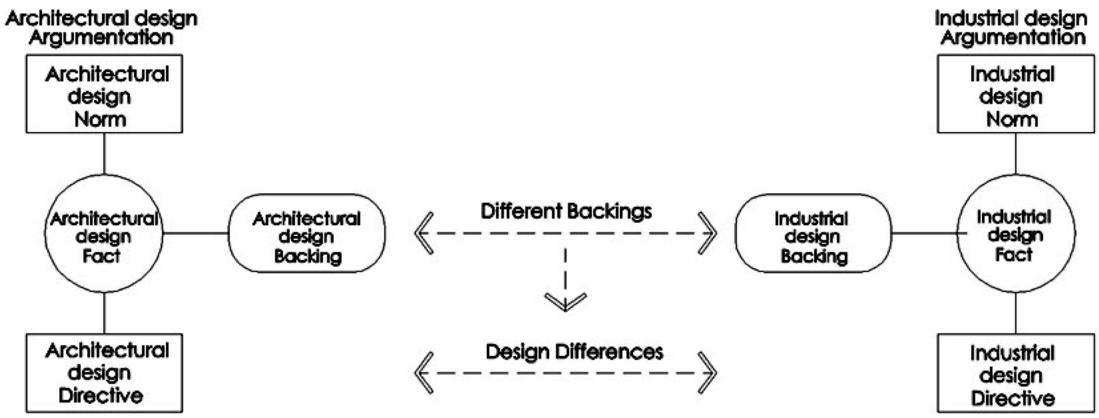

Figure 9: A diagram of Type II Design Difference formation

Figure 9 shows that the design difference arises because architectural and industrial design has different directives (A-D and I-D) to the same norm (N). It is because they have different backings, which largely depend on their beliefs that are influenced by their learnt knowledge, pervious experiences, and training backgrounds.

In the solution of Type II Design Difference, there are also two conditions. In the first condition, in terms of the different backings that support their different directives, one party has more authority then the other. Jeng (1995) argued that the conflict between individuals who want the same thing but must settle for different things is most likely to escalate unless it has a ceiling to prevent escalation and the only restraint on escalation is fear of the consequences. In the same way, the directives generated by a party with stronger backing usually wins due to more reliable consequences brought about by its directives.

In the second condition, the backings are equally strong. Then to solve it, Type II Design Difference has to be transformed to Type I Design Difference (Coombs and Avrunin 1988). It usually takes both parties' cooperation to transform from Type II to Type I Design Difference (Jeng 1995). As conflict situation in a collaborative design, whose goal is producing the best possible product exists, belongs to *cooperati*ve conflict situation, it is generally not difficult to transform the design difference from Type II to Type I.[21] Therefore, it can be concluded that to better understand the formation of Type I Design Difference in collaborative design process will help resolve both two types of design differences. Consequently the differences between norms of architectural and industrial design should be examined.

2.3. A comparative study of architectural and industrial design

Based on the understanding of a design problem as an ill-defined problem, it is widely believed that "designing designs the questions as well as the answers" (Gross el al. 1987,

[21] According to Klein and Lu (1989, 168), "Conflict situations can be divided into two categories: competitive conflict situations and cooperative conflict situations". In the first situation, "each party has solely their own benefit in mind and has no interest in achieving a globally optimal situation if such a solution provides them no added personal benefit"; while in the later situation, "the parties are united by the superordinate goal of achieving a globally optimal solution, which often requires sacrificing personal benefit in the interest of increased global benefit". And the strategies for cooperative conflict resolution "typically involve techniques, such as compromise or abandonment of less important goals, oriented towards finding as mutually beneficial a solution as possible" (Klein and Lu 1990, 169).

53).[22] Due to the limitation of time, cost, and mental resource, a designer usually cannot exhaustively search and scrutinize the possible problem space. Therefore, the problem space must be narrowed to a certain reasonable size by design constraints. Gross el al. (1987, 55-57) proposed that "constraints and objectives can often be interchanged. Moreover, the constraints are not completely known. They are not just part of the problem. They are all of the problem… We can describe a design problem or task as a collection of constraints and relations on attributes of the object to be designed. Then to design is to describe constraints and to specify an object that satisfies all these constraints."[23] In this way, it can be said that design constraints can be related to norms, which are goals or objectives to be achieved in a design process. In this study the terms *constraint* and *norm*, are used interchangeably.

Design constraints reflect the structures of design problems. Archer (1964, 4) argued that it is the nature of the predominating constraints that determines whether the problem is called architecture, engineering, applied science, industrial design or art and craft, although all these terms are more or less vague in their comprehensiveness, and tend to overlap or merge into one another at their fringes.

[22] Gross et al. (1987, 54) proposed that "design and designing are not the same. Design is domain bound; designing seems rather less so."

[23] According to Gross el al. (1987, 56-57), "Constrains are the rules, requirements, relations, conventions, and principles that define the context of designing. There are many constraints on a design and they come from different sources. Constrains are imposed by nature, culture, convention, and the marketplace. Some are imposed externally, while others are imposed by the designer. Some are site-specific, others not. Some are the result of higher-level design decisions; some are universal, a part of ever design. … We can describe a design problem or task as a collection of constrains and relations on attributes of the object to be designed. Then to design is to describe constraints and to specify an object that satisfies all these constrains".

According to Yoon (1992), some design problems are under-constrained, with no limit to the range of feasible solutions. Some design problems are over-constrained, having too many constraints to be satisfied. The former usually needs to be narrowed down by designers through exploring the constraints in the design process, while in the latter some of the constraints have to be relaxed. In whichever case, the constraints of a design problem cannot be adequately described at the initial stage of design. Therefore, design is not only the process of satisfying existing constraints but also the discovery and accommodation of new constraints arising throughout the process.

As having been discussed in section 1.3.4, a different party may have different problem space, the structure of which can be reflected by the design constraints considered by them. In a collaborative design process designers from each party will exchange their considerations and requirements in terms of the design, which results in the addition of or deletion of some existing constraints. Consequently, the design problem space of each party will be changed. Ideally, the overlapping area of the different design problem spaces can be enlarged through the collaboration.

In this section we will firstly draw a general comparison between architectural and industrial design in terms of the issues such as the nature of products and the practical commissions of designers with reference to project-related product design. All these factors have substantial influence on the design constraints. Following that, a comparative study of design constraints between architectural and industrial design will be presented.

2.3.1. Nature of building and product

	Building	Product
Context sensitivity	Location-dependent, context-sensitive	Location-independent, but not context-independent
Scale	Both exterior and interior are important to users	Only exterior is important to users
Interaction	User interacts with architecture mainly by experiencing its space	User interacts with product mainly through its interface
Functionality	Multi-functionality	Mono- functionality
Life-cycle	Long life-cycle	Short life-cycle
Flexibility	High-flexibility	Low-flexibility

Table 1: A comparison of nature of building and product

Table 1 above shows a comparison between the nature of building and product (Liem and Li, 2001, Jager 2002). Basically, a building is a three-dimensional structure separating outside from inside to create a shelter for human beings. Although architecture is more than simply a shelter, the idea of enclosure is a very fundamental issue to architecture. As a manmade habitat, a building can be regarded as a kind of system, which is defined as a set of interrelated and interdependent parts arranged in a manner that produces a unified whole. A system is always made up of other systems and comprised of another. According to these principles, a building as a system, is part of a higher-level system, say its immediate environment. On the other hand, a building itself is a high-level system to those subsystems which compose a building such as structural system, enclosure system, and so on. In other words, a building sets the environment for its user as well as products or materials applied. Thus basically users interact with a building mainly through experiencing its spaces and both exterior and interior of the building are important to the users. At the same time, the site is the external environment of a building (see Figure 10). However, the external environment of a building is usually much larger than the site. It can be divided roughly into general environment (urban context) and specific environment (location) (Yeang 1999, 8).[24] Thus a building is highly location-dependent and context-sensitive. Here the term *context* includes two folds of meaning. One refers to physical urban context, and the other refers to cultural, social, and political context.

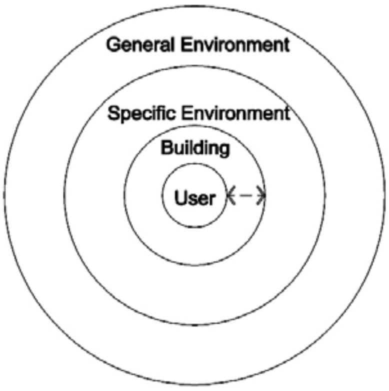

Figure 10: Relationship between user, building, and environment

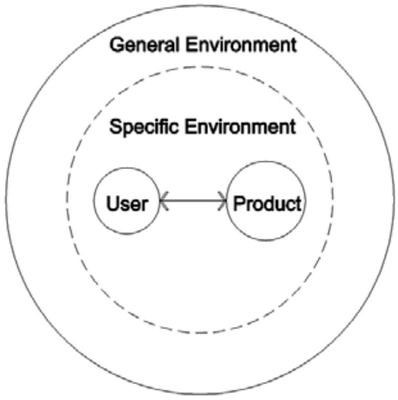

Figure 11: Relationship between user, product, and environment

Due to the relative small scale of a product, the relationship between a product and its user is more emphasized the interface (See Figure 11). A product is often designed for a general environment, which cannot be controlled by designers. However, a product can still be designed for a certain context, although not for a specific location. Thus, it can be said that a product is location-independent, but not context-independent.

Building project-related products have dual nature. On the one hand, they have the characteristics of products. On the other hand, they have to work as an integral part of buildings and therefore have to fulfill architectural design requirements. Unlike a project-independent product, which is designed for a general building environment, a project-

[24] According to Yeang (1999), "at the level of specific environment, two categories of factors should be considered. One is physical site constraints and opportunities, including urban context, accessibility, and views; another is environmental response, including solar exposure and natural day lighting."

related product is designed to fit in a particular building project and work as an integral part to respond to the specific environment around the building (see Figure 12). Thus, a project-related product should be both location-dependent and context-sensitive.

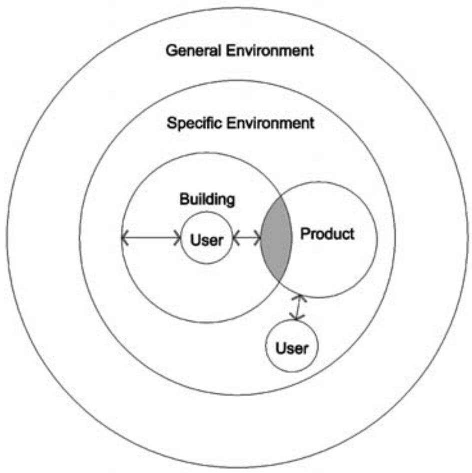

Figure 12: Relationship between user, product, building, and environment

The factors with regard to functionality, life-cycle, and flexibility are close related. The lifecycle of architecture is usually longer than that of a product since the cost and time in the former are often much more than those in the latter. Thus a product is usually mono-functional (or oligo-functional) and purchased to serve a present need. Therefore, it is not necessary to include functional flexibility in designing consideration (Jager 2002). On the contrary, due to its large scale, long life-cycle, and high cost, a building is multi-functional and often expected to continuously cater for individual and changing needs.

In terms of a project-related product, usually it is a systematic solution which comprises several components. The complexity of functionality and flexibility of a project-related product is varied and lies between that of the building they serve and the components that make of it.

2.3.2. The requirements of practice

	Architectural design process	Industrial design process
Emphasis of practice	Treating project-related products as building components manufactured in a factory, emphasizing on the building as a whole.	Treating project-related products as products applied in building, concentrating on the individual components.
Design practice process	*A: Inception* *B: Feasibility* *C: Outline proposals* *D: Scheme design* *E: Detail design* *F: Production information* *G: Bills of quantities* *H: Tender action* *J: Project planning* *K: Operations on site* *L: Completion* *M: Feed-back*	*1. Planning* *2. Concept development* *3. System-level design* *4. Detail design* *5. Testing and refinement* *6. Production ramp-up*
Functions of design team	Architectural design Structural engineering design Mechanical and electrical engineering design Building construction	Marketing Industrial design Engineering design Manufacturing

Table 2: A comparison of practice requirements

Given the different commission, there are several different requirements for architectural and industrial design practice. Table 2 above shows some differences in terms of the emphasis on practice, design practice process, and functions of design team.

2.3.2.1. Emphasis of practice

Architectural design usually treats project-related products as building components manufactured in a factory, emphasizing on the building as a whole, while industrial design treats them as products applied in building, concentrating on the individual components (see Figure 13). As a result, architectural and industrial design may have different considerations in practice.

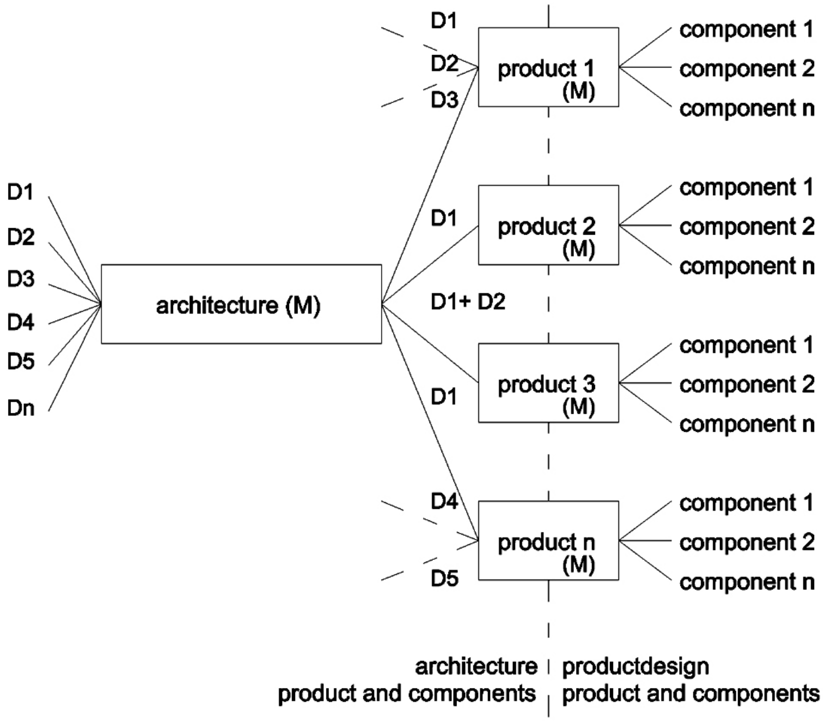

Figure 13: Architecture designing and product designing (Jager 2002)

Eekhout (1989, 43) proposed that architectural design is more concerned with the topology of building elements, or in other words, the positioning of these elements in space, and is less concerned with properties, technical behaviour and repetitive use for other buildings. With the re-allocation of design responsibilities, “the position of the architect is gradually reduced to overall design and overall 3-D management, leaving much detail design work and drawings in the new materials and building techniques to advisors and specialist-producers” (Eekhout 1989, 33).

2.3.2.2. Design practice process

An architectural practice process comprises a series of stages from inception to completion.[25] Because the case in this study is chosen from the practice in Singapore, the procedure proposed by the Royal Institute of British Architects (RIBA) in its publication *the Architect's Job Book* is adhered to. It consists of a twelve-stage procedure (Beaven et al. 1989):

A: Inception
B: Feasibility
C: Outline proposals
D: Scheme design
E: Detail design
F: Production information
G: Bills of quantities
H: Tender action
J: Project planning
K: Operations on site
L: Completion
M: Feed-back

Besides the traditional building process, in which architects are leaders on behalf of clients, nowadays there are many different ways of structuring the building process, such as Design & Build and the Turnkey solutions. In different kinds of processes, some stages may be adjusted and recurrent. In an architectural design process, which comprises project-related product design, a two-stage tender procurement is always adopted to let an manufacturer and his industrial design team get involved in at early stages of the architectural design process.

[25] The practice process is usually influenced by many exterior practical factors in specific industry context in each country. Therefore, the design procedures in different countries' architectural practice may vary slightly in their chronological sequence. However these variations are less significant than the overall sequence, which is fairly uniform. Further despite the exact names of each stage are varied, there is nevertheless substantial commonality in content. Thus, we can choose one design procedure as a representative.

According to Ulrich and Eppinger (2000, 14), "a product development process is the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product". Accordingly, they proposed a six-phase procedure:

1. *Planning*
2. *Concept development*
3. *System-level design*
4. *Detail design*
5. *Testing and refinement*
6. *Production ramp-up*

The development process is a generic process, which is similar to the process used in a *market-pull* situation. Particular processes will differ in accordance with the unique context of a firm or a project.

As has been discussed in Chapter 1, in the design and development process of project-related products, some stages of architectural practice process overlap and are substituted by industrial design practice process. Haviland (1998, 463) proposed a chart of the options for allocating design responsibilities as shown in Figure 14.[26]

[26] He claimed that even for the first option, where both conceptual and detail design are conducted by professional consultants, a good deal of detailed component and assembly design are still shifted to manufacturers, suppliers, and specialist trade contractors through the mechanisms of required shop drawing, samples, and product submission.

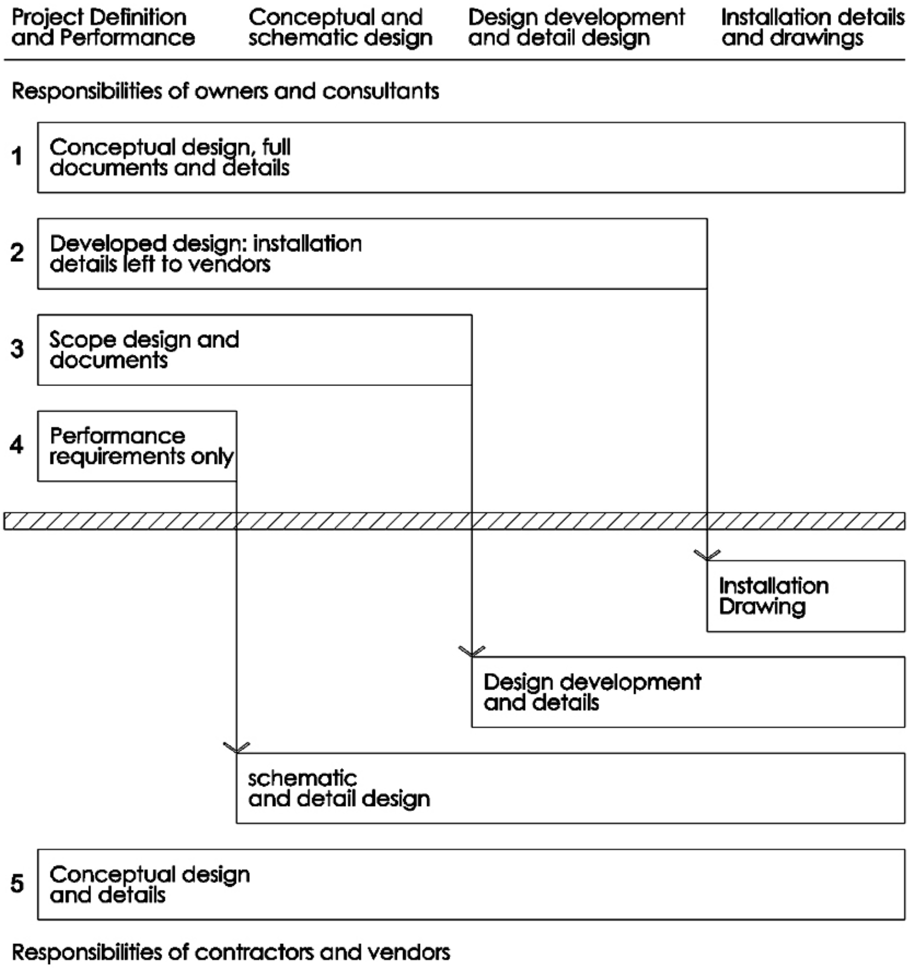

Figure 14: Options for allocating design responsibilities (Haviland 1998, 464)

As one kind of products, a prefabricated building product distinguishes its industrial market from the usual consumers market by the durability of the product, the method of choosing a product, and the nature and abilities of the client (Eekhout 1989).[27] In the

[27] Eekhout (1989, 47-48) proposed following properties of building products market:

- *Products usually are building components or building elements, fitting into a larger product (the building) by assembly and erection.*
- *The product is bought for a specific purpose in the building industry: for example the primary function of space structures is to form roof structures.*
- *The product is bought by other organisations via quotations and tenders. Main contractors may buy on price, but usually architects will finally decide, more on quality and appearance of the offered product.*

development processes of project-related products, marketing aspects can be omitted because the specific architectural design team of the project is the client, with whom an industrial design team can hold a dialogue directly.

2.3.2.3. Functions of design team

In practice, both architectural and industrial design requires team-work. In this study, it is assumed that an architectural design team refers to those employed in a consulting firm, while an industrial design team is employed in a manufacturing firm, which is the most common institutional setting for product development (Ulrich and Eppinger 2000, 3). This is usually the common setting in practice in terms of building project-related product design and development.

For an architectural design team, four basic functions are important: architectural design, structural engineering design, mechanical and electrical engineering design, and building construction. Architects are usually the leaders of the design teams.

For industrial design, Ulrich and Eppinger (2000, 3) pointed out three functions that are central to a product development project: marketing, design, and manufacturing. They

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- *The industrial marketing research is concerned with the needs of the building industry (to be seen as the collective of principals, architects, structural engineers and main contractors), keeping in mind the goals of the building industry.*
- *On the industrial market, clients usually are experts. They will base their decisions on quality and other objective criteria of primary function; secondary functions can sometimes influence the final choice.*
- *The product is usually bought in large quantities by a limited number of clients. This causes a different sales and promotion strategy compared with the consumers market."*

further explained that the marketing function mediates the interactions between the firm and its customers, including the identification of product opportunities, the definition of market segments, and the identification of customer needs. The design function includes industrial design, which emphasizes aesthetics, ergonomics, and user interfaces aspects, and engineering design, which emphasizes mechanical, electrical, and software aspects. The manufacturing function includes designing and operating the production system, purchasing, distribution, and installation. Different individuals within these functions form an industrial design team. The leader can be drawn from any of the functions of the firm.

Based on the understanding of the different nature of buildings and products as well as the different requirements of architectural and industrial design practice, we will proceed to compare the differences in architectural and industrial design thinking in terms of design constraint.

2.3.3. Differences in design constraint

Table 3 shows design constraints imposed on architectural design and industrial design respectively, summarized based on Tzonis and Oorschot (1987)'s classification of architectural norm. These design constraints may be interdependent, not exhaustive, and not mutually exclusive.

	Constraints of architectural design	Constraints of Industrial design
1. Aesthetic	**A1.1 Site context** A1.1.1 Social, cultural, and political context A1.1.2 Urban context **A1.2 Views** **A1.3 Exterior design images** **A1.4 Interior design images**	**I1.1 Exterior design images**
2. Ergonomic	**A2.1 Circulation patterns** User flow and equipment and material transport **A2.2 Spaces** **A2.2.1 Indoor spaces:** what spaces are needed to support facility users' activities? **A2.2.2 Outdoor spaces:** what are the requirements for outdoor space in terms of amenities, landscape development and preservation, and enhancement of existing natural features? **A2.3 Ambient environmental factors** **Indoor**: A2.3.1 Circulation discomfort A2.3.2 Lighting A2.3.3 ventilation A2.3.4 Variety A2.3.5 Acoustical A2.3.6 Thermal comfort A2.3.7 Cleanliness and sense of order **Outdoor:** A2.3.8 Disorientation A2.3.9 Microclimatic A2.3.10 Contact with ground and green A2.3.11 Weather exclusion **A2.4 Durability and maintainability** A2.4.1 Durability A2.4.2 Maintainability **A2.5 Convenience, safety, and security**	**I2.1 Ease of use** I2.1.1 Ease of manufacturing I2.1.2 Ease of assembly **I2.2 Durability and maintainability** I2.2.1 Durability I2.2.2 Maintainability **I2.3 Quality of User interactions** **I2.4 Novelty of user interactions** **I2.5 Safety** I2.5.1 Safety for manufacturing I2.5.2 Safety for assembly

Table 3: A comparison of design constraints

	Constraints of architectural design	**Constraints of Industrial design**
3. Economic	**A3.1 Cost of materials** **A3.2 Cost of construction** **A3.3 Cost of service** A3.3.1 Cost of energy A3.3.2 Cost of maintenance A3.3.3 Cost of cleaning A3.3.4 Cost of grounds-keeping A3.3.5 Cost of mechanical transportation **A3.4 Circulation cost** **A3.5 Space efficiency** **A3.6 Rentability** **A3.7 Durability**	**I3.1 Cost of materials** **I3.2 Cost of manufacturing** **I3.3 Cost of transportation** **I3.4 Cost of assembly** **I3.5 Cost of service** I3.5.1 Cost of maintainance
4. Technical	**A4.1 Construction** A4.1.1 Materials A4.1.2 Dimensional suitability A4.1.3 Strength and stability A4.1.4 The bearing capacity of the site **A4.2 Flexibility:** Change and growth	**I4.1 Marketing** **I4.2 Manufacturing** I4.2.1 Materials I4.2.2 Dimensional suitability I4.2.3 Strength and stability I4.2.4 Designing and operating the production system I4.2.5 Purchasing I4.2.6 Distribution I4.2.7 Installation I4.2.8 transportation **I4.3 Flexibility**

Table 3: A comparison of design constraints (continued)

2.4. Summary

This chapter provided a cognitive framework to explore design differences in collaboration between architectural and industrial design processes. It includes three parts. Firstly, the central part of the framework, the *Kernel of Conceptual System* (Tzonis et al. 1978), was introduced as a suitable representation of design reasoning process with the key elements and structure for beliefs, judgement, and decision making. Secondly, based on the *Kernel of Conceptual System* (Tzonis et al. 1978) and Coombs and Avrunin

(1988)'s *Structure of Conflicts*, two types of design differences were derived and discussed. Finally, a general comparison of architectural and industrial design was given in two aspects. One is different nature of buildings and products in terms of context sensitivity, scale, interaction, functionality, life-cycle, and flexibility. The other is different practice requirements of architectural and industrial design practice in such aspects as emphasis of practice, design practice process, and functions of design team. Based on these findings, design constraints, which form the structures of design problems, were further compared.

This cognitive framework will serve as a guide to better understand a collaborative design process in a specific case study in the following chapters, specifically on what, when, and how design differences arise. Next chapter will give a detailed study of design differences, which arose in the different collaborative design scenarios of a project-related product design for a newly-established project in Singapore.

Chapter 3: A case study - Esplanade -Theatres on the Bay, Singapore

Design differences in the roof cladding system design: a description at a product and an activity level

In the previous chapter a cognitive framework was structured to clarify design differences in collaboration between architectural and industrial design processes. This chapter will study in detail these design differences based on a case study of a specific project in Singapore. The question of what kinds of design differences can arise in the collaboration are intended to be answered. To begin with, the reason of selecting this specific project will be expounded and clarified. Following this, a general description of the project will be given to form an overall picture of the roof cladding system as a building project-related product with reference to its design product and design practice process. Three distinctive scenarios in terms of collaboration between the architectural and industrial design process are critically identified and described. Finally, based on a comparison of design products in the three design scenarios, four design differences will be identified and tabulated.

3.1. Objective and method of the case study

3.1.1. Objective of the case study

The objective of conducting the case study is to understand the collaborative design process of a project-related product in the following aspects:

1. *What kinds of design differences can arise in the collaboration?*

2. *When do these design differences arise?*
3. *How do these design differences arise?*

3.1.2. Selection Criteria of a specific project for the case study

For this case study, a project in Singapore, Esplanade-Theatres on the Bay, is chosen according to the following criteria:

1. *The roof cladding system of the project is a typical representative of project-related products.* The whole system is composed of a space-frame structure with glazing and sun-shadings on it. It embraces both system products and special products. The former include the MERO space-frame structural system and the connection of the glazing layer, the latter include the tailor-made sun-shading layer, which are specifically designed and manufactured for this particular project.
2. *The design of the roof cladding system involves collaboration between an architectural design process and an industrial design process.* In this project, an architectural design team from Singapore DP Architects Pte. Ltd. (DPA) works closely with an industrial design team from Germany MERO GmbH & Co (MERO), who carries a contractual responsibility for the design and building of the roof cladding system as a specialist subcontractor. Both companies are well-known in Singapore and the region. DPA has conducted many large-scale projects and won several awards.[28] MERO is an established manufacturer based in Germany and has many branches in the world, including Singapore. Their products, especially structural glazing products, have been adopted in several projects in

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[28] Suntec City, Bugis Junction, Far East Square, The Bayshore Condominium, Orchard MRT station, etc.

Singapore.[29]

3. *It is a successful example of contemporary collaborative design of project-related products.* Because what is discussed here is contemporary practice of architecture and product design, the case chosen should be a recent project. The design of Esplanade began in 1992 and the construction was completed in 2002.[30]

3.1.3. Data sources of the case study

The data regarding the design process of the roof cladding system were gathered from the following sources:

1. *Interviews with the architect, manufacturer-designer, and cladding consultant.*
    a) Author's interview with Mr. Vikas M. Gore (the project director of Esplanade-Theatres on the Bay, DPA)
    b) Author's interview with Alan J. Brookes (Cladding consultant, Atelier one)[31]
    c) Correspondence with Mr. Claus Kaspar (Project manager, MERO)
2. *Collation of documentations*
    a) Lyric theatre and concert hall design report prepared by Atelier one and Atelier ten (October, 1995)
    b) Tender documentation proposed by DPA and Atelier one (March, 1996)[32]

[29] Jurong Point Extension project, Changi Airport Terminal project, and Rendezvous Hotel project.

[30] "It was the first time that an arts centre of such a scale was to be built in Singapore. The project was the largest since the National Theatre in 1963 and the conversion of Kallang Cinema into Kallang Theatre in 1986." (The Esplanade Co Ltd. 2002, 16)

[31] Atelier one is a London based engineering firm and worked as the cladding consultant in this project.

c) Design development drawings by MERO (August,1998)

d) A presentation report on the roof cladding system by DPA (September, 1999)

3. *Collation of visual data, which include photographs, sketches, and drawings.*

4. *Collation of relevant information from publications*

3.2. Description of the project

Esplanade-Theatres on the Bay is a new performing arts centre in Singapore. It is built on a six-hectare site by the marina bay in Singapore's historic Civic District, near the mouth of the Singapore River (Please refer to Appendix A, Figure A-1 to A-3 for illustrations). In phase I, which was completed in 2002, the project incorporates a 1800-seat concert hall and a 2000-seat lyric theatre. The latest technological equipments and finest acoustics within its halls adopted by Esplanade would make it rank among the top performing arts facilities in the world (ABC, 2001). The design of the Esplanade reflects a harmonic balance between man and nature. Its unique layout is largely represented by the roof cladding system, which is a building project-related product (Please refer to Appendix A, Figure A-4 for illustration).

[32] Atelier Ten is an associated firm of Atelier One. In this project, Atelier Ten was responsible for the computational analysis of the environmental impact of the sun.

3.2.1. System products and special products in the roof cladding system

In the final design the two distinctive domes mainly comprise three sets of key components: 1) a space-frame structure, 2) a glazing layer with 10,508 double-glazed laminated glass panels, and 3) a sun-shading layer with 7,139 fixed aluminum sunshades. (Please refer to Appendix A, Figure A-5 for illustration). All these products were prefabricated in the factory and assembled on site.

According to Mr. Gore, "The geometric scheme is a square grid, like a mesh spread over a surface. The analogy I often cited is a kitchen sieve. Where the mesh bunches up at four points and stays square at other points along the edge, there's a gradual shift from a very narrow shape to a square shape and back to a narrow shape. And when this is draped over a more undefined shape than a hemisphere, you get quite a complex and organic look and feel to it" (The Esplanade Co Ltd 2002, 18). The aluminum sun-shading panels, "which are isometric triangles folded symmetrically from its apex line", are mounted on this complex mesh (Tan 2002). "The fins are angled at various degrees: at times they are hung half-open to the glazing beneath them, yet at other places, they are hung so closely to the shell of the shells that they seem to form a patchwork armour. The angles – which determine the degree of effectiveness of the sun-shading fins – are carefully executed to maximize the views to the surrounding buildings and the sea as well as to shield against the sunlight in the east-west orientation. The result is occurrences of interesting gradual transitions of the sun-shading fins – from half-open to near-fully closed – which takes place at a flowing pace along the dome's shell, drawing additional attention to its already arresting shape. The sun-shading fins' colours vary from tones of grayish-white to champagne-gold hues, depending on the angle at which sunlight is reflected off them." (Tan 2002)

Figure 15: Exterior view of the two domes

Figure 16: The roof cladding system

3.2.2. Design practice process

The design of the roof cladding system (Design Alternative of Architectural Design) was initiated by architectural practice process by DPA. They adopted a Two-stage tendering procurement strategy in this project.[33] After they finished a primary detail design of the cladding system, a tender was called and four manufacturers were asked to submit their initial tenders based on the Design Alternative of Architectural design. From the initial tenders, an alternative (Design Alternative of Industrial Design) offered by a manufacturer, MERO, was chosen. Consequently, MERO was appointed as the cladding contractor, who

[33] Because clients usually expect subcontractors to be selected by competitive tender, more often than not, the specialist subcontractor's design work usually takes place after he has committed himself to a price for the work and has signed a contact (AJ 1991, 37). Therefore, to introduce a manufacture and its industrial design team into a design process at an early stage, two-stage tendering procurement strategy is often adopted. "With two-stage tendering, several manufacturers or contractors would be asked to submit initial tenders at an early stage in the project, based on outline designs produced by the project design team. Particular organisations would then be chosen at this stage and asked to develop their designs and approaches to achieve the project deliverables. Effectively this second stage is a negotiated contract, based on the first stage tender." (Gibb 1999, 192)

was responsible for the design and building of the roofing structure of the Concert Hall and Lyric Theatre (The Esplanade Co Ltd 1998, 7). In this way, some design responsibilities were transferred from the architectural design team to the industrial design team, i.e. from DPA to MERO. However, DPA could still reject and ask for more modification for MERO's proposals. Thus a new design solution (Design Alternative of Collaborative Design) was formed by the collaboration between MERO and DPA. (For detail practice processes of the cladding system, please refer to Appendix B)

3.3. Three scenarios of collaborative design

In the design process of the roof cladding system there are two sub-processes, i.e. non-collaborative design process and collaborative design process. The former reflects non-collaborative scenario. The latter comprises two design scenarios in terms of collaboration between architectural and industrial design processes, i.e. semi-collaborative scenario and full-collaborative scenario (see Figure 17). These three scenarios will be discussed in the following sections.

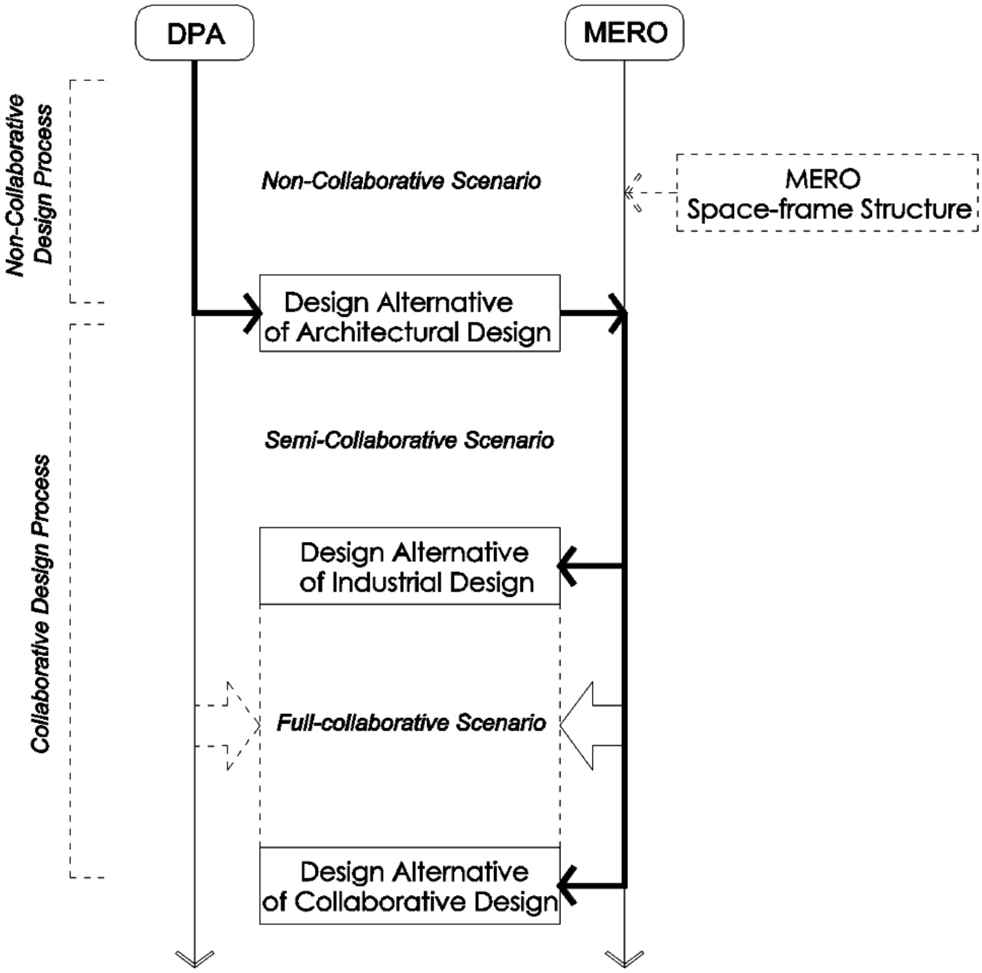

Figure 17: Three scenarios in the design process of the roof cladding system

3.3.1. Non-collaborative design process: non-collaborative scenario

In the first scenario of this project, an architectural design team from DPA initiated the design of the cladding system and worked alone without any particular requirements from a specific industrial design team. It is called a *non-collaborative scenario*.

In a *non-collaborative scenario*, there are no direct design differences between these two parties. However, architectural design may consider some constraints from an industrial design perspective based on the experience and knowledge available. Usually there exist some potential design differences, especially in buildability and manufacturing aspects. These potential differences will either become explicit in the later stages of design or result in poor design if they remain implicit.

Besides the one conducted by the architectural design team in this project, another non-collaborative process conducted by an industrial design team, i.e. the design process of MERO space-frame structure, also need to be considered. Although this process is not specifically for Esplanade, it has considerable influences on the roof cladding system design of this project.

3.3.2. Collaborative design process: semi-collaborative and full-collaborative scenario

In the second scenario, the requirements from the architectural design team were forwarded to an industrial design team in the form of tender documentation. Although there was no further interaction between the architectural and industrial design team, the former's specific requirements on the product had imposed constraints on the industrial design process. Therefore, it is called a *semi-collaborative scenario*.

In a *semi-collaborative scenario*, design differences may arise because an industrial design team works with the constraints imposed by an architectural design team, but there is no necessary discussion between these two parties. Therefore, a design alternative of an industrial design process may still have several design differences compared with that of an architectural design process.

In the third scenario, an architectural design team and an industrial design team worked together. However, it was the industrial design team who initiated design proposals at this stage because of the formal contractor situation. The architectural design team may either accept or reject the initiative proposals from the industrial design team or ask for more modification. In this way, they would consider and impose constraints on each other's design, and achieve an integration, optimization, or compromise together. Therefore, it is called a *full-collaborative scenario*.

3.4. Design differences in the design of the roof cladding system

Four major design differences in the design process of the roof cladding system can be identified.[34] As having been introduced in Section 3.2.1., the roof cladding system comprises three sets of key components, i.e. the support structure, the glazing layer, and the sun-shading layer. Design difference 1 resides in the support structure design, design difference 2 in the connection design of the glazing layer, and design difference 3 and 4 in the connection design of the sun-shading layer and in the shape design of sun-shading panels respectively.

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[34] The designs of Esplanade project proposed in this dissertation are summarized based on the author's interviews with Mr. Vikas M. Gore (the chief architect of this project, DPA) and Alan J. Brookes (Cladding consultant, Atelier one), correspondence with Mr. Claus Kaspar (Project manager, MERO), Lyric theatre and concert hall design report prepared by SMP Atelier one, Atelier ten in October 1995, Tender documentation proposed by DPA and Atelier one in March 196, a presentation report on the cladding system by DPA in September 1999, and design development drawings by MERO in August 1998.

As having been discussed in the Section 1.2.2, the development processes of project-related products generally involve two kinds of processes, i.e. the customization process of a system product and the development process of a special product (see p.19). For this project, on the one hand, MERO already had a developed space-structure system and a glazing system before they were involved. The existing systems were adjusted to fit the specific requirements from DPA to design the first two sets of components, i.e. the support structure and the glazing layer. In this sense, the design processes of the support structure and the glazing layer fall into the discussion of customization processes of system products. And the design difference 1&2 can be seen as system-product-related design differences. On the other hand, the sun-shading layer is a newly designed product specifically for the project. Thus, the design process of the sun-shading layer falls into the discussion of development processes of special products. And the design difference 3&4 can be seen as special-product-related design differences. Before analyzing their formations (please refer to chapter 4), the four design differences are presented first.

3.4.1. Design differences in customization of system products

3.4.1.1. The support structure

In the non-collaborative design process the architectural design team from DPA established a solution as two single layer tube structures with steel tubes up to 230 mm in diameter. These structures follow the equal length link mesh geometry to form two domes that fit the volumes of the theatres respectively. All steel member connections of the structure are fully welded on site (see Figure 18 and Figure 20).

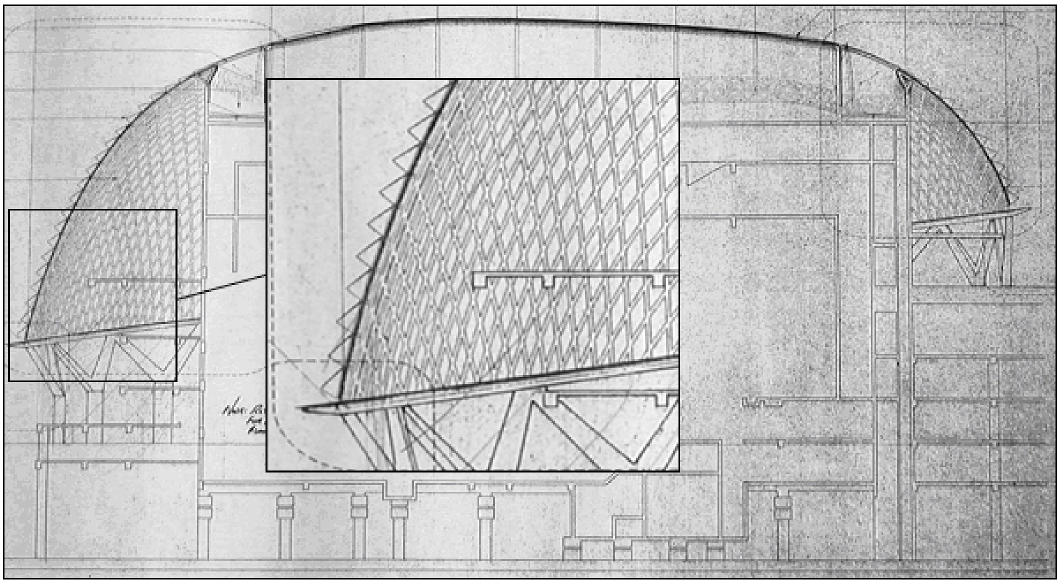


Figure 18: Support structure design in the non-collaborative scenario: Section of concert hall across East and West (Source: DP Architects)

Prior to MERO's formal participation in this specific project their traditional MERO space-frame structural system had been well developed as one of the earliest prefabricated space-frame systems with a wide range of applications. It consists of only two basic components, i.e. ball nodes and members made of hollow round sections. The geometrical system based on the node is simple. In combination with a series of different members arranged according to the principle of a geometric progression, it can be made to fit a great variety of shapes. By strictly limiting the number of different member types, MERO was able to produce them in series.[35]

In the semi-collaborative scenario MERO applied the space-frame structural system to fit the geometry of the roof envelop proposed by DPA. Two 900mm deep double layer space-frame structures with steel tube 50 to 60 mm in diameter were proposed. Most steel

[35] http://www.mero.de/Bausysteme/index.html (22 June 2003).

members are MERO standard member products, and all the members can be prefabricated in a factory and assembled on site without welding. Thus, design difference 1 in terms of the structure design arose in the semi-collaborative scenario (see Figure 19 and Figure 21). In the full-collaborative scenario the design mostly kept the previous solution of the semi-collaborative scenario (see Table 4).

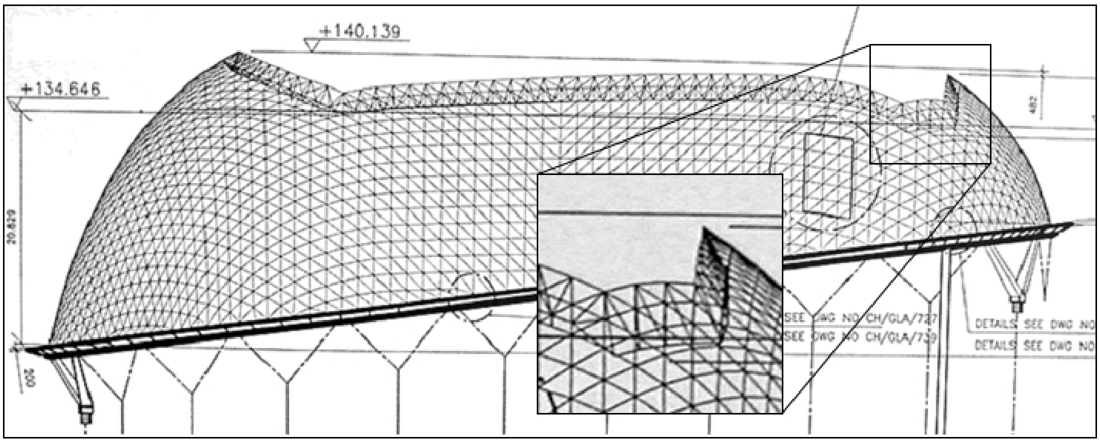


Figure 19: Support structure design in the semi-collaborative scenario: concert hall layout (Source: MERO GmbH & Co)

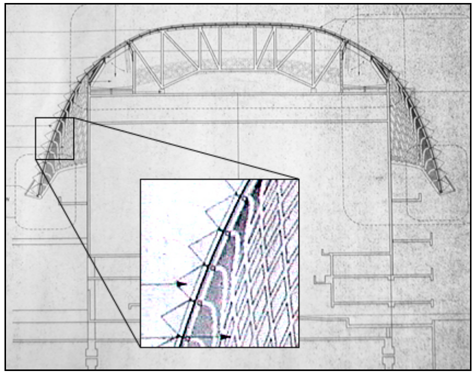
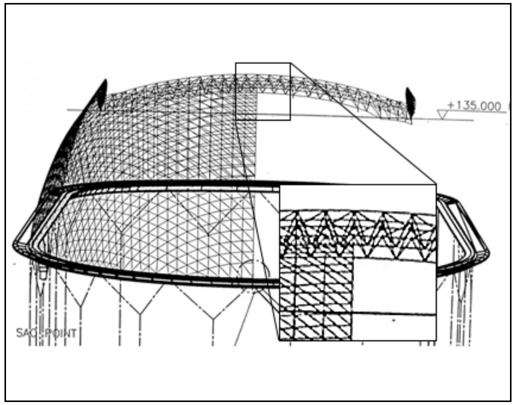
Non-collaborative design process	**Collaborative design process**	
Non-collaborative scenario	Semi-collaborative scenario	Full-collaborative scenario
The single tube structure with steel tubes up to 230 mm in diameter and with all steel member connections fully welded on site.  **Figure 20:** Support structure design in the non-collaborative scenario (Source: DP Architects)	Two 900mm deep double layer space-frame structures with steel tube 50 to 60 mm in diameter. Most steel members are MERO standard member products (MERO-KK and MERO-NK members), and all members are prefabricated in a factory and assembled on site without welding.  **Figure 21:** Support structure design in the semi-collaborative scenario (Source: MERO GmbH & Co)	The design mostly keeps the previous solution in the semi-collaborative scenario.  **Figure 22:** Interior view of the support structure (Source: Author)

Table 4: Description of design difference 1: design of the support structure

3.4.1.2. The glazing layer

In the non-collaborative design process the glazing layer of the cladding system is composed of aluminum framed sealed double glazed units held 100mm off the face of the underlying structural steel lattice by aluminum brackets (see Figure 23).

In the semi-collaborative scenario the glazing layer of the cladding system is composed of 28.76mm double glazed units, mounted on the gasket that sits directly on the MERO flat-top node, with steel disk seals and holds glass panel corners (see Figure 24). Thus, design difference 2 in terms of connection design of the glazing layer arose in the semi-collaborative scenario. Alike, when proceeding to the full-collaborative scenario the design mostly kept the previous solution of the semi-collaborative scenario (see Figure 25, Table 5).

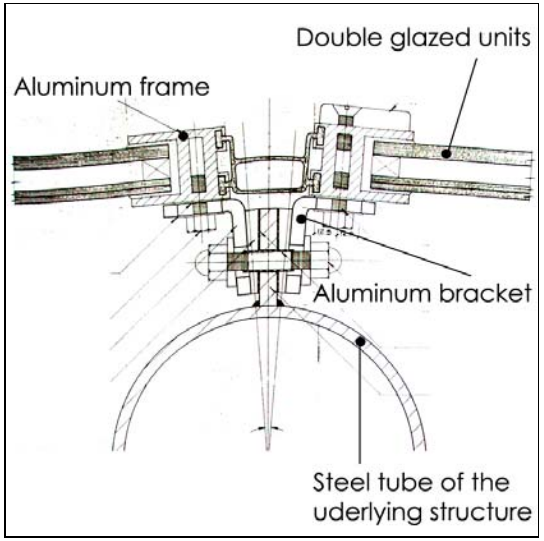
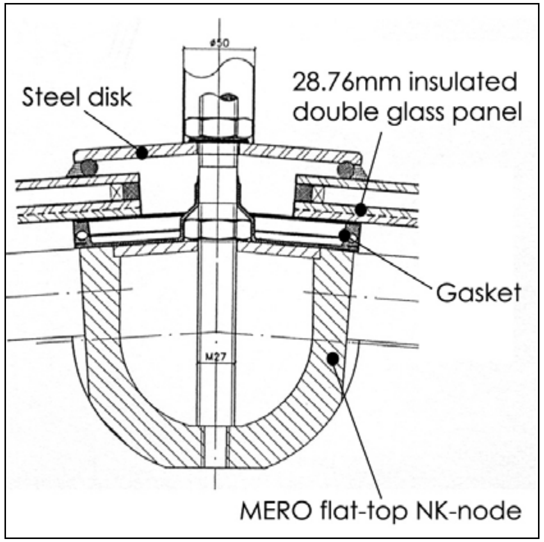
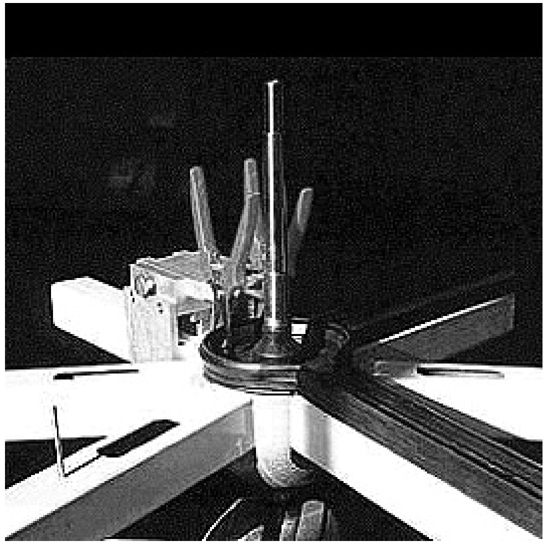
Non-collaborative design process (Non-collaborative scenario)	**Collaborative design process**	
	Semi-collaborative scenario	Full-collaborative scenario
Using aluminum framed sealed double glazed units held 100mm off the face of the underlying structural steel lattice by aluminum brackets.  **Figure 23:** Connection design of the glazing layer in the non-collaborative scenario (Source: DP Architects)	Using the gasket sits directly on the MERO flat-top node, with steel disk seals and holds glass panel corners.  **Figure 24:** Connection design of the glazing layer in the semi-collaborative scenario (Source: MERO GmbH & Co)	The design mostly keeps the previous solution in the semi-collaborative scenario.  **Figure 25:** A prototype of the connection of the glazing layer in the full-collaborative scenario(Source: DP Architects)

Table 5: Description of design difference 2: connection design of the glazing layer

3.4.2. Design differences in development of special products

As to the sun-shading layer design in the non-collaborative scenario, aluminum sun-shading panels, which are isometric triangles folded symmetrically from its apex line and conically bent at the top, are mounted on the uniform equal length link mesh formed by the support structure. The angles of sun-shading panels are at various degrees, depending on their positions (see Figure 26, Figure 29, and Figure 32).

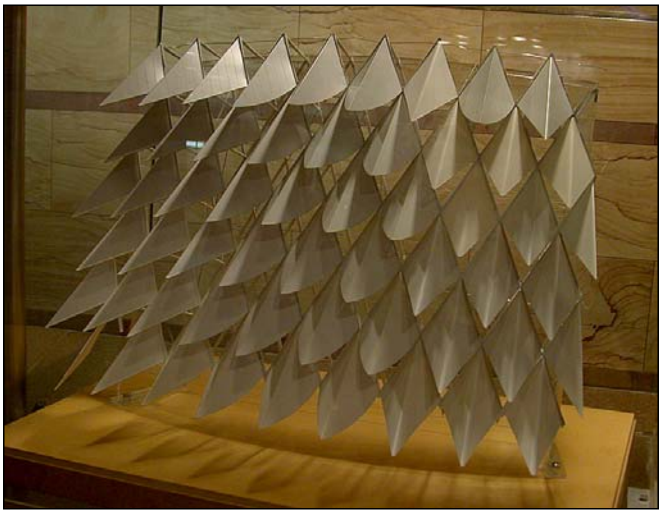


Figure 26: A model of the sun-shading layer design in the non-collaborative scenario (Source: Author)

In the semi-collaborative scenario, most parts of the design solution previously proposed by DPA were kept in the alternative solution. However, the joint design were changed to be a ball joint, and the sun-shading panels were folded by a straight bent at the top (see Figure 30 and Figure 33).

The design of the sun-shading layer in the full-collaborative scenario kept changing, unlike that of the other two sets of key components, the support structure and the glazing layer. In the final design aluminum sun-shading panels, which are isometric triangles folded symmetrically from its apex line and cylindrically bent at the top with a diameter of 120mm, are mounted on the equal length link mesh formed by the support structure with a ball joint system (see Figure 31 and Figure 34). The free edge of the panel is bent down slightly as a triangular kink. The angles of sun-shading panels are at various degrees, depending on their positions (See Figure 27 and Figure 28). Thus, design difference 3 in terms of connection design of the sun-shading layer and design difference 4 in terms of shape design of sun-shading panels arise in both semi- and full-collaborative scenarios (see Table 6 and Table 7).

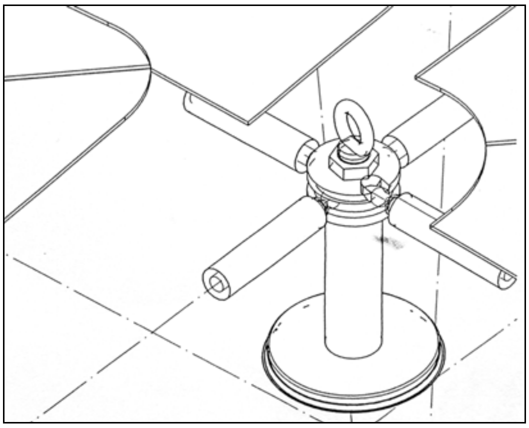


Figure 27: Connection design of the sun-shading panels in the full-collaborative scenario: the ball joint system (Source: MERO GmbH & Co)

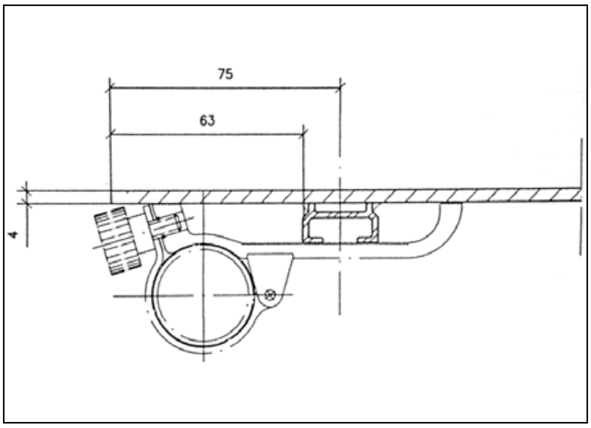


Figure 28: Connection design of the sun-shading panels in the full-collaborative scenario: section of side fixing of shading panel (Source: MERO GmbH & Co)

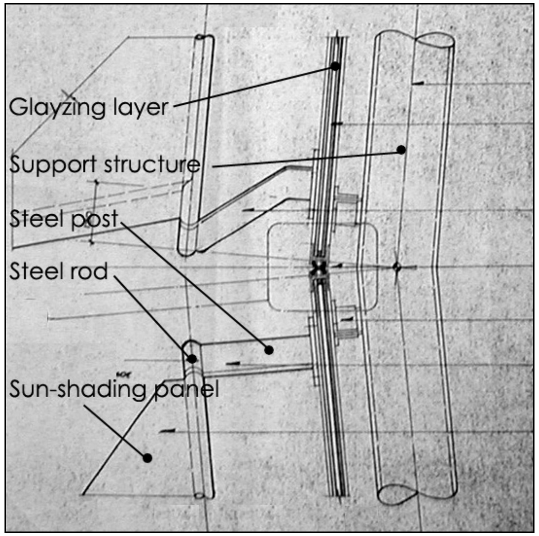
<table>
<tr><th rowspan="2">Non-collaborative design process
(Non-collaborative scenario)</th><th colspan="2">Collaborative design process</th></tr>
<tr><th>Semi-collaborative scenario</th><th>Full-collaborative scenario</th></tr>
<tr><td>Using rods to hold the sun-shading panels and the rods are supported by posts that amounted on the glazing layer.</td><td>Using a fixed ball joint to hold the rods, on which the sun-shading panels are fixed.</td><td>Using a ball joint system, with four rods fixed into one ball joint. And sunshades are fixed on the rods.</td></tr>
<tr><td>


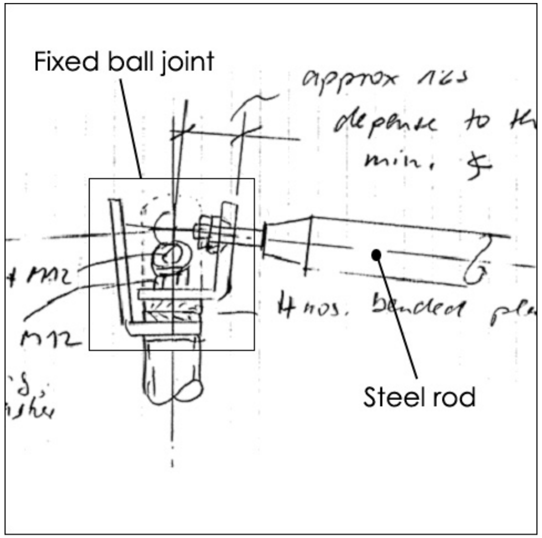
Figure 29: Connection design of the sun-shading panels in the non-collaborative scenario (Source: DP Architects)</td><td>


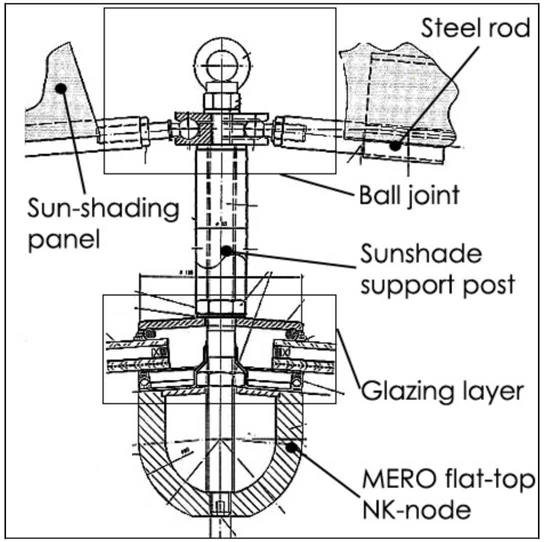
Figure 30: Connection design of the sun-shading panels in the semi-collaborative scenario (Source: MERO GmbH & Co)</td><td>


Figure 31: Connection design of the sun-shading panels in the full-collaborative scenario (Source: MERO GmbH & Co)</td></tr>
</table>

Table 6: Description of design difference 3: connection design of the sun-shading panels

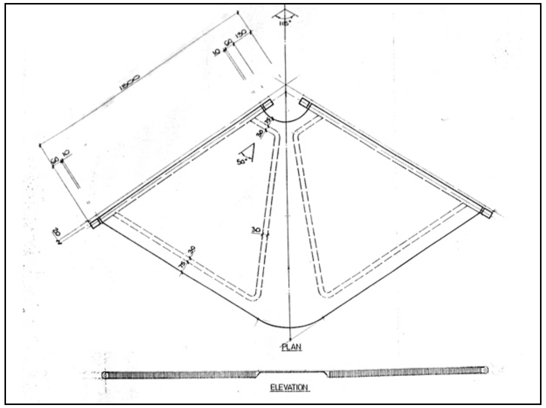
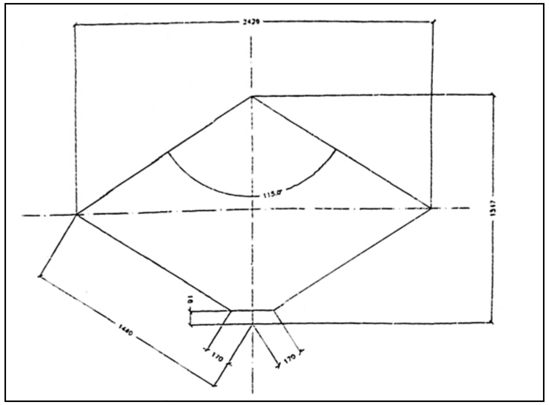
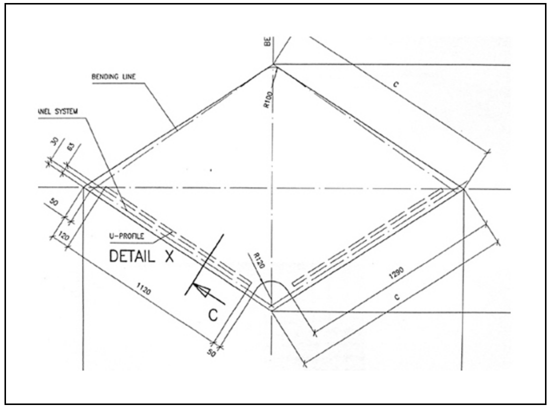
Non-collaborative design process (Non-collaborative scenario)	**Collaborative design process**	
	Semi-collaborative scenario	Full-collaborative scenario
The panels are conically bent at the top.  **Figure 32:** Shape design of the sun-shading panels in the non-collaborative scenario (Source: DP Architects)	The panels are straight bent at the top.  **Figure 33:** Shape design of the sun-shading panels in the semi-collaborative scenario (Source: MERO GmbH & Co)	The panels are cylindrically bent at the top.  **Figure 34**: Shape design of the sun-shading panels in the full-collaborative scenario (Source: MERO GmbH & Co)

Table 7: Description of design difference 4: shape design of the sun-shading panels

3.5. Summary

Esplanade theatres on the bay in Singapore is chosen as a case study in this research, because the roof cladding system of the project is a typical and contemporary representative of project-related products and involves intensive and successful collaboration between architectural and industrial design processes. The cladding system of Esplanade is a customized product developed specifically for this project as a one-off design. It is initiated by an architectural design process and completed by a collaborative operation. A two-stage tendering procurement strategy is employed in the design and development of the roof cladding system by introducing a manufacturer and his industrial design team to the early stages of the design process. In doing so, the responsibilities of design development and detail design are transferred from the architectural design process to the industrial design process, or in other words, from a project design team to a product design team. Three scenarios according to the degree of collaboration, i.e. nil-, semi-, and full-collaborative scenario, were identified in the design process of the roof cladding system. In the three distinctive scenarios, different design outcomes under different contexts of collaboration were discerned. Four tabulations of design differences in terms of two types of project-related products, i.e. system products and special products were proposed respectively. The next chapter will aim to explore the causality of these specific design differences under the customization process of system products and the development process of special products respectively. How these design differences are formed will be clarified with the cognitive framework proposed in Chapter2.

Chapter 4: Understanding design difference in collaborative design

Exploring how design differences arise within the cognitive framework: an analysis and discussion at a thinking level

Chapter 3 introduced the roof cladding system design of Esplanade-Theatres on the Bay as a case study of a specific project-related product. Three design scenarios in the design process were identified and the design differences between architectural and industrial design were presented. This chapter attempts to answer the question how these design differences arose. By applying the cognitive framework proposed in Chapter 2, two kinds of design processes closely resided in project related products will be examined, i.e. customization process of system products and development process of special products. The *Kernel of Conceptual System* (Tzonis et al. 1978), firstly, provides a core analytic framework to map explicitly architectural and industrial design reasoning processes respectively. Based on it, different design constraints considered and different design beliefs possessed by each design team are compared in the light of categories of difference formulated in Chapter 2. Thus, the formation of design differences will be revealed and analyzed. Furthermore, the analysis inspires to draw a few implications for the future collaborative design. However, it should be noted that due to the complexity of reasoning processes for any practical design project, what being presented below is to generalize some key points concerned with the main structures of the design reasoning processes. As far as concerned, it is impossible and unnecessary to list exhaustively all other arguments which are probably made in the design process.

4.1. Analytical framework of the case study

Before proceeding to analyze the design differences arise in the design reasoning processes, the analytical framework adopted and the symbols used in the case study will be explained first.

The entire analysis of the design reasoning processes fundamentally follows the structure of design argumentation defined in the *Kernel of Conceptual System* (Tzonis et al. 1978) introduced in Chapter 2 (p.36-38). As having been discussed, in the *Kernel of Conceptual System* (Tzonis et al. 1978), a deontic branch, which relates a directive to a norm, and a factual branch, which comprises a backing and a base components, constitute the basic kernel of an argumentation, i.e. an argument unit. More importantly, the deontic branch of the kernel can be linked together and combined within a hierarchy of reasoning process, in which a directive of a higher level becomes a norm of the next lower level (it can be called a “derived norm”). In this way, each argument units can be connected in a sequence (please refer to Figure 5 in page 38). For the case study, design reasoning processes are expressed in this kind of chains of argumentations. To represent the key components of the argumentations, i.e. norm, directive, fact, backing, and base, the prefixes “AD- ", which stand for “Architectural Design”; and "ID-", which stand for “Industrial Design”, are employed to differentiate the argument components. Through comparing architectural and industrial design processes, the formation of design difference can be analyzed at thinking level.

4.2. Design differences in the customization process of system product

In the case study, the formation of design difference 1(i.e. structural design, please refer to Table 4 in page 72) and design difference 2 (i.e. connection design of the glazing layer, please refer to Table 5 in page 74) have strong relation to the application of the MERO space-frame structural system, which is a typical example of project-related system products. Therefore, design difference 1&2 will be examined in the concept of system-product-related difference.

4.2.1. Design difference 1: structural design

In the architectural design process conducted in the non-collaborative scenario the overall layout of the roof cladding system was defined. The directive of using two domes that fit respectively the internal volumes of the concert hall and the lyric theatre are generated from three prominent norms (please refer to Table 8 in page 85-86). One considered in the aesthetic aspect by the architectural design team (i.e. DPA) is that the geometry of the building should be gentle in order to minimum the aggressive visual impact induced by such large building volumes. The other two in ergonomic aspect are related to the shape and thermal comfort of the spaces created by the roof envelops. The spatial forms of the support structures should provide grand interior gathering and circulation spaces, and simultaneously, suitable comfort level with minimum of energy consumption.

The other important directive is to use uniform link length mesh shells. As the dominant part of the whole project, the design of the roof envelop should reflect the multi-culture feature of Singapore as well as be cotemporary architecture. To fulfill these norms, DPA generate the directive to use geometric mesh shells of square grid, which is an abstract pattern generalized from texture of Southeast Asian culture. In addition, DPA takes into consideration the norms related to the standardization of roof cladding components and minimization of costs. As a result, DPA developed the geometric mesh shells of square grid further into uniform length link mesh shells.

Combining the two directives above, the overall layout of the roof cladding structure comes into being, i.e. using structures with all steel members following an equal length link mesh geometry to form two domes that fit the volumes of the theatres.

To realize this layout, two norms in technical aspect were added. They are reducing the weight of the support structure and achieving the full shear and moment continuity. As a result, a single layer structure was adopted to achieve the lightness and the connections of all steel members would be welded on site to achieve the stability of the whole structure (please refer to Figure 18 in page 70 and Figure 20 in page 72).

In the non-collaborative design reasoning process mapped out above, norms considered by the architectural design team, some were from an industrial design perspective based on their learnt knowledge of industrial design. Nevertheless, the design solution from the architectural design team apparently will have potential difference with that from the industrial design team (i.e. MERO) since no specific requirement was put forward from the latter.

In the semi-collaborative scenario, an entirely different alternative was generated. The directive (i.e. using structures that follow the equal length link mesh geometry to form two domes that fit the volumes of the theatres) generated by the architectural team, was kept by the industrial design team as a norm. However, to fulfill this derived norm together with the other two technical norms (i.e. achieving the lightness as well as full shear and moment continuity of the structures), MERO had a different directive, to adopt their traditional system product, i.e. MERO space-frame structural system (please refer to Figure 19 in page 71 and Figure 21 in page 72).

Although MERO space-frame structural system is not specifically designed for this project, the application of the system in the collaborative process of this project has significant influence on the design of the roof cladding system. Therefore, the considerations behind the design of MERO system should be highlighted. Most norms considered by MERO belong to ergonomic and economic aspects, such as the easiness and safeness of installation and manufacturing, the structural effectiveness compared with the amount and quality of steel required, and the easiness for transportation. One of the most prominent aspects considered by MERO is the cost of the system. It has a high priority for profit-driven manufacturing company and also significant for the competency of the system product in market. In addition, the design of the system also achieves the elegancy of component design in aesthetic aspect, as well as high accuracy, simplification, and flexibility of the components in technical aspect. With these qualities, MERO space-frame structural system can be applied and adjusted to fit different building layouts. MERO's knowledge and experience give them backings that MERO space-frame structural system can fulfill the norms proposed by DPA.

Design Constraint	Description of Norms			Practice Process (Collaborative Scenarios)		
				Non	Semi	Full
1. Aesthetic	**Site context (A1.1)**	Social, cultural, and political context (A1.1.1)	**AD-Norm**: *The geometry of the building envelopes should reflect the multi-culture feature of Singapore.*			
			AD-Norm: *The geometry of the building envelopes should reflect that it is a very contemporary building.*			
		Urban context (A1.1.2)	**AD-Norm**: *The geometry of the building envelopes should be gentle and not aggressive.*			
	Exterior design images (I1.1)		**ID-Norm:** *The structure components should be designed elegantly.*			
2. Ergonomic	**Spaces (A2.2)**	Indoor Spaces (A2.2.1)	**AD-Norm:** *The building envelopes should create foyer spaces for the two theatres.*			
	Ambient environmental factors (A2.3)	Indoor Thermal comfort (A2.3.6)	**AD-Norm:** *The geometry of the building envelopes should reduce cooling load of the interior spaces.*			
	Ease of use (I2.1)	Ease of assembly (I2.1.2)	**ID-Norm:** *The structure members should be installed easily and fast.*			
	Safety (I2.5)	Safety for assembly (I2.5.2)	**ID-Norm:** *The structure members should be installed safely.*			
3. Economic	**Cost of Construction (A3.2)**		**AD-Norm:** *Reducing the types of sun-shading panels and glass to minimum.*			
			AD-Norm= ID-Norm: *Simplifying the structural members.*			
	Cost of service (A3.3)	Cost of Energy (A3.3.1)	**AD-Norm:** *The geometry of the building envelopes should reduce cooling load of interior spaces.*			

Legend (grey band) The continuity of the consideration for the norms proposed by the architectural design team

(hatched band) The continuity of the consideration for the norms proposed by the industrial design team

Table 8: Norms in design difference 1: structure design

Design Constraint	**Description of Norms**			**Practice Process (Collaborative Scenarios)**		
				Non	**Semi**	**Full**
	Cost of materials (I3.1)		**ID-Norm:** *The design of structure should be high structural effective compared with the amount and quantity of steel required.*			
	Cost of transportation (I3.3)		**ID-Norm:** *The structure members should be easy to be transported from factory to site.*			
	Cost of assembly (I3.4)		**ID-Norm:** *The structure components should be installed easily and fast.*			
4. Technical	**Construction (A4.1)**	Materials (A4.1.1)	**AD-Norm:** *Achieving the lightness of the structure.*			
		Strength and stability (A4.1.3)	**AD-Norm:** *Achieving full shear and moment continuity of the structures.*			
	Manufacturing (I4.2)	Designing and operating the production system (I4.2.4)	**AD-Norm: =ID-Norm:** *Simplifying the structural components.*			
		Installation (I4.2.7)	**ID-Norm:** *Achieving high accuracy of the steel components.*			
		Transportation (I4.2.8)	**ID-Norm:** *The structure components should be easy to be transported from factory to site.*			
	Flexibility (I4.3)		**ID-Norm:** *The design of structure should be highly flexible in terms of varying geometrical and structural conditions and requirements.*			

Legend The continuity of the consideration for the norms proposed by the architectural design team

The continuity of the consideration for the norms proposed by the industrial design team

Table 8: Norms in design difference 1: structure design (continued)

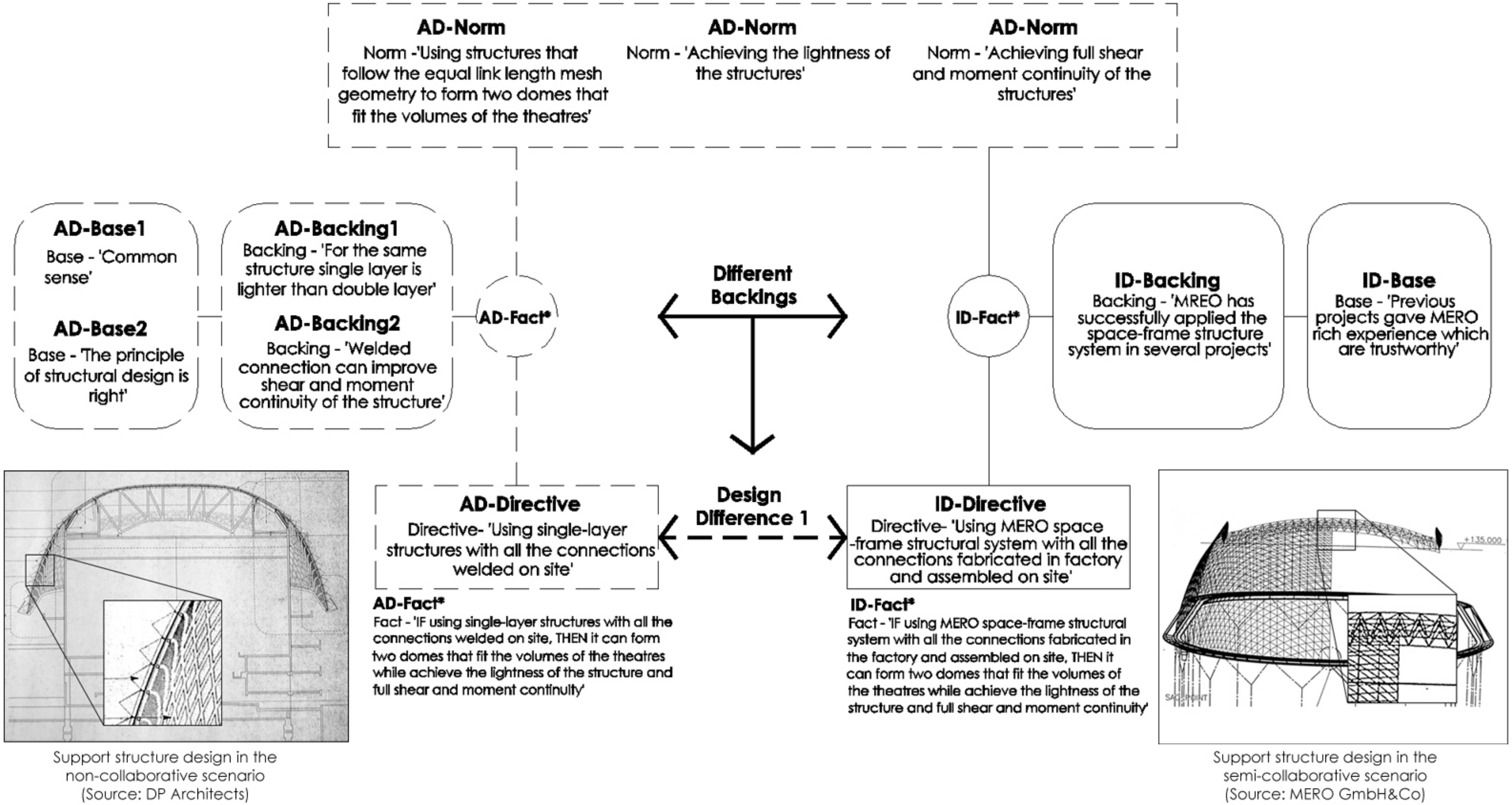


Figure 35: A diagram of design difference 1 (i.e. structure design) formation

Based on above analysis, it is can be seen that the reason why DPA and MERO have different directives to the same norms is that they have different backings (See Figure 35). MERO's specialized knowledge of and rich experience in application of space-frame structure give them stronger backings, which guarantee the possible advantages brought about by the application of MERO space-frame structural system. Consequently, the authority possessed by the MERO provided by their strong backings influenced the decision making when design differences arose in the design process.

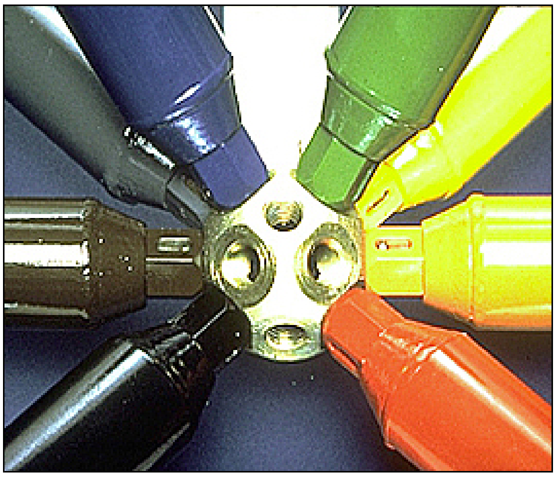


Figure 36: MERO space-frame structure node proposed by MERO in semi-collaborative design scenario (Source: MERO GmbH & Co)

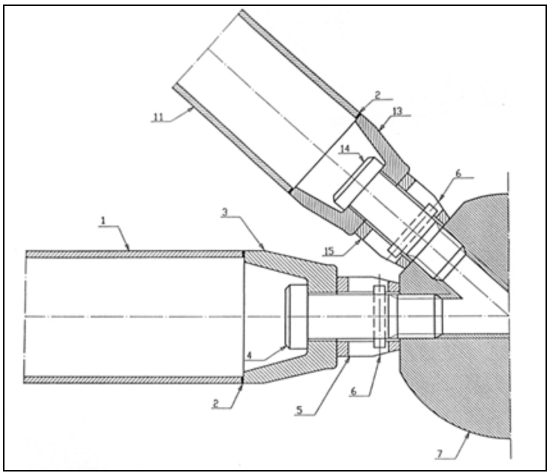


Figure 37: Connection design of the support structure in the full-collaborative scenario: bottom node section with MERO-KK members (Source: MERO GmbH & Co)

As a result, in terms of the support structure design, although in the semi-collaborative design scenario the design solution from the industrial design team has significant design differences with the one from the architectural design team, there was no conflict arose. The architectural design team generally accepted the design product of the semi-collaborative scenario, the design in the full-collaborative scenario mostly kept the previous solution. From Figure 36 and Figure 37 above it can be seen that the connection design of the support structure in the full-collaborative scenario has no major difference with the one proposed by MERO in semi-collaborative design scenario, i.e. MERO space-frame structure node. In other words, no major changes occurred in the full-collaborative scenario except some dimension and location adjustments of the structure members to fit the particular geometry of the building.

4.2.2. Design difference 2: connection design of the glazing layer

The final connection design of the glazing layer integrates three components together: the gasket, the connection of the sun-shading panels, and the upper node of the support structure, i.e. MERO NK-node. More importantly, this jointing system can be seen as a sub- or secondary system product attached to main MERO space-frame structural system and the design of the connection has a close relation with the design of the main support structure.

The directive of using a glazing system for external envelope of the roof cladding is generated from the aesthetic norms related to the social and political context considered by DPA (please refer to Table 9 in page 91). As a national theatre, it is a performing arts centre for people, which should be "democratic rather than elitist". Through using a glazing layer, physically, it allows view in and out, and symbolically, it stands for political transparency. In addition, transparent external façade can also fulfill another aesthetic norm related to view, i.e. providing people with the magnificent views of the civic district around the site.

However, to respond to the increasing energy consumption brought about by the application of the glazing layer and to achieve thermal comfort of the interior spaces, a glazing system comprising glass panels that can fulfill the OTTV value was developed as well as another sun-shading layer above the glazing layer (the design of the sun-shading layer will be discussed in section 4.3).

Then how to integrate the glazing façade with the underlying structure? Two norms were prominent for DPA when considering the connection design of the glazing layer with the structure. One in the ergonomic aspect is that the glazing layer should shelter internal structure from the effects of weather; another from aesthetic aspect, the aesthetic effects of the connection design should be concise. To fulfill these norms, the directive in terms of connection design generated by DPA is that using a glazing system that comprises aluminum framed sealed double glazed units held 100mm off the face of the underlying structural steel lattice by aluminum brackets (please refer to Figure 23 in page 74).

Design Constraint	Description of Norms			Practice Process (Collaborative Scenarios)		
				Non	Semi	Full
1. Aesthetic	**Site context (A1.1)**	Social, cultural, and political context (A1.1.1)	**AD-Norm:** *creating a performing center for people, which should be "democratic rather than elitist".*			
	Views (A1.2)		**AD-Norm:** *Provide people the magnificent views of the Civic District around the site.*			
	Exterior design images (A1.4 =I1.1)		**AD-Norm = ID-Norm:** *The aesthetic effects of the connection design of the glazing layer should be concise.*			
2. Ergonomic	**Ambient environmental factors (A2.3)**	Indoor Thermal comfort (A2.3.6)	**AD-Norm:** *The design of building envelop should achieve thermal comfort of the interior spaces.*			
		Outdoor weather exclusion (A2.3.11)	**AD-Norm:** *Sheltering internal structure from the effects of weather.*			
	Ease of use (I2.1)	Ease of assembly (I2.1.2)	**ID-Norm:** *The connection design of the glazing layer should be easy to be assembled.*			
3. Economic	**Cost of service (A3.2)**	Cost of Energy (A3.2.1)	**AD-Norm:** *The design of building envelops should minimize cooling load of the interior spaces.*			
4. Technical	**Manufacturing (I4.2)**	Installation (I4.2.4)	**ID-Norm:** *The connection of glass and support structure should be easy to be assembled.*			
			ID-Norm: *The connection design of the glazing layer should be easy to be manufactured with low manufacturing tolerance.*			

Legend
The continuity of the consideration for the norms proposed by the architectural design team
The continuity of the consideration for the norms proposed by the industrial design team

Table 9: Norms in design difference 2: connection design of the glazing layer

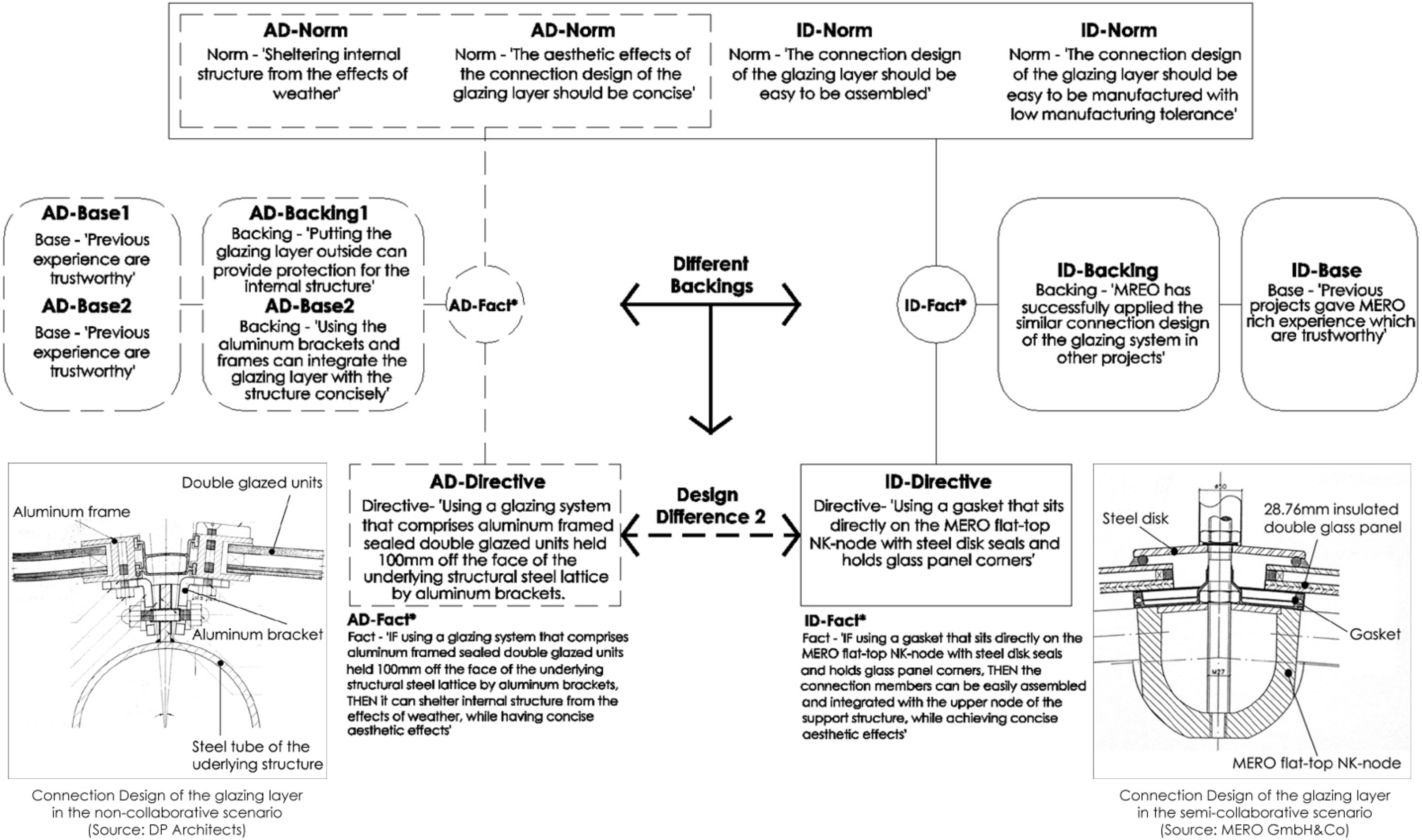


Figure 38: A diagram of design difference 2 (i.e. connection design of the glazing layer) formation

In semi-collaborative scenario besides norms about ambient environmental factors and aesthetic effects proposed by DPA, MERO added some new norms associated with assembly and manufacturing of the connection in both ergonomic and manufacture aspects (see Figure 38). To MERO, the connection should be designed to be easily assembled and manufactured with low manufacture tolerance. As a result, MERO generated a new directive that efficiently combines three components, i.e. the gasket, the connection of the sun-shading panels, and the upper node of the support structure. In MERO's alternative, the gasket sits directly on the MERO flat-top NK-node and the connection of sun-shading panels is also integrated with it (please refer to Figure 24 in page 74).

From above analysis, it can be seen that in the connection design of the glazing layer, DPA and MERO have different directives because they have both different norms and different backings. However, the different backings due to the adoption of MERO space-frame structural system are more important factors in this design difference. It is noted that in the semi-collaborative scenario with the acceptance of MERO space-frame structural system, the design of its upper node, i.e. MERO flat-top NK-node, highly influenced the connection design of the glazing layer. Or, in other word, the jointing system together with the MERO flat-top NK-node is customized in the collaborative design process. As in the structure design, this new directive from MERO was accepted by DPA without further differences arising in full-collaborative scenario.

4.2.3. Advantage of collaboration: Design difference 1&2

With the alternative of the industrial design team, the diameter of the steel members of the support structure can be reduced from 230mm to 60mm. This would have a dramatic impact on aesthetic effects of the structure, especially from the interior. Because it adopts a system product that possesses the characteristics of mass production with low manufacturing tolerance, the alternative of the industrial design team reduces over 20% of the cost compared with that of the architectural design team. MERO's quotation is also the lowest among the four manufacturers who tendered for this project. In addition, since all the components are prefabricated in a factory and can be assembled on site conveniently, safely, and fast, the accuracy of the connection is increased. Meanwhile, the duration for on site work is reduced dramatically. Nearly 3 months was saved for the construction of the whole roof cladding system.

Through being integrated with the upper node of the support structure, i.e. the standard MERO-NK node, the connection design of the glazing layer is simplified and becomes more efficient compared with the solution of the architectural design team. In this way, the cost and time of installation are reduced. In addition, due to its simplification, this connection design produces a more concise and elegant appearance and more accurate connection compared with the complicated design of the architectural design team (see Table 10).

	Design Difference Type	**Non-collaborative design process** (Non-collaborative scenario)	**Collaborative design process**		Advantages of collaboration
			Semi-collaborative scenario	Full-collaborative scenario	
Design Difference 1: Structure design	**Type II**	Two single layer structures with steel tube up to 230 mm in diameter. All steel member connections are fully welded on site.	Two 900mm deep double layer space-frame structures with steel tube 50 to 60 mm in diameter. Most steel members are MERO standard member products that can be prefabricated in a factory and assembled on site without welding.	The design mostly keeps the previous solution in the semi-collaborative scenario.	**Cost** • A over 20% cost saving due to the application of MERO space-frame structural system **Time** • Decrease of time due to a fast and comparatively easy and safe installation with high accuracy **Quality** • Improvement in aesthetic appearance of the support structure, especially from interior • Improvement in aesthetic appearance of the connection • Improvement in the accuracy of steel structure components
Design difference 2: Connection design of the glazing layer	**Type II**	Using aluminum framed sealed double glazed units held 100mm off the face of the underlying structural steel lattice by aluminum brackets	Using a gasket sits directly on the MERO flat-top node, with steel disk seals and holds glass panel corners.	The design mostly keeps the previous solution in the semi-collaborative scenario.	**Time** • Decrease of time due to a fast and comparatively easy and safe installation with high accuracy **Quality** • A more concise and elegant appearance and more accurate joining due to the simplification of the connection design

Table 10: Key design differences in customization of the system products and advantages of collaboration: Design difference 1: structure design & Design difference 2: connection design of the glazing layer

4.3. Design differences in the development process of special product

The prominent sun-shading layer of this specific project is a special product, in the design of which neither the architectural design team nor did the industrial design team have experience before. Therefore, there are no priorities in their backings. Design difference 3 & 4 (i.e. connection design of the sun-shading layer and shape design of the sun-shading panels) in the design of the sun-shading layer can be seen as design differences that arise in the development process of a special product.

Like difference 1 & 2, design difference 3 & 4 arise in the semi-collaborative scenario when the industrial design team provides different solutions from those by the architectural design team in the non-collaborative scenario. However, unlike difference 1 & 2, design difference 3 & 4 were not accepted by the architectural design team. In the full-collaborative scenario, the design differences are integrated and the conflicts induced are resolved.

As having been discussed in the last section, the application of a glazing external façade brings about the problem of strong sunshine and high consumption of energy. Therefore, to achieve thermal comfort and to minimize the cooling load of the interior spaces, besides using glasses that can fulfill certain OTTV value, a sun-shading layer was also added above the glazing layer. On the other hand, while sheltering the interior space from sun-shine, the sun-shading layer should also minimize its block of view. To fulfill these two norms, DPA generated a directive of using a series of aluminum sun-shading panels mounted on the equal length link mesh formed by the support structure and the angles of the panels are of various degrees, depending on their positions.

4.3.1. Design difference 3: connection design of the sun-shading panel

In non-collaborative design scenario DPA considered more about the ergonomic aspect in terms of building performance and maintenance (see Table 11 in page 99). To satisfy the norms of easy accessibility for cleaning up the components and the norm of providing sufficient ventilation on the glazing surface, it leads to the solution that the sun-shading panels and the glazing panels are mounted on different layers by using rods to hold the panels, while the rods are supported by posts that amounted on the glazing layer (please refer to Figure 29 in page 77).

While in the semi-collaborative scenario one norm in both aesthetic and ergonomic aspect considered by MERO is that the connection design of the sun-shading panels should be integrated with the upper node of the structure, i.e. MERO NK-node. Moreover, besides rethinking two norms from the architectural perspective, the norm most concerned by MERO is that the connection should be made easily be replaced individually without influencing other sunshades. As a result, a new directive is reestablished by MERO to replace the one from DPA (please refer to Figure 39 in page 100). It is to use a steel extrusion on the underside of the sun-shading panel to fix the lower edge of the panels with the rods, which are held by a ball joint fixed on a pin that is extruded from the top of the MERO NK-node (please refer to Figure 30 in page 77).

MERO's directive has more flexibility in maintaining and replacing the sun-shading panels compared with DPA's original one. However, DPA pointed out that the size of the ball joint is too big in MERO's solution. In the full-collaborative scenario, thus, DPA introduces another norm, i.e. the appearance of the connection should be more elegant, to refine MERO's solution (see Figure 40 in page 101). By integrating this norm into those considered by them previously, MERO improved the design into a ball joint system. It is to use a steel extrusion on the underside of the sun-shading panel to fix the lower edge of the panels with the rods, which are held by an advanced ball joint system fixed on a pin, which is extruded from the top of the MERO NK-node (please refer to Figure 27and Figure 28 in page 76).

Design Constraint	Description of Norms			Practice Process (Collaborative Scenarios)		
				Non	**Semi**	**Full**
1. Aesthetic	**Views (A1.2)**		**AD-Norm:** *The design of the sun-shading layer should minimize the block of view outside.*			
	Exterior design images (A1.3 = I1.1)		**AD-Norm:** *The design of the sun-shading layer should create continuous visual effects for the sun-shading panels.*			
			AD-Norm: *The appearance of the connection should be more elegant.*			
			ID-Norm: *The fixing design of the sun-shading panels should be integrated with the upper node of the structure, i.e. MERO NK-node.*			
2. Ergonomic	**Ambient environmental factors (A2.3)**	Ventilation (A2.3.3)	**AD-Norm:** *Proving necessary ventilation for the glass surface.*			
		Indoor Thermal comfort (A2.3.6)	**AD-Norm:** *The design of building envelops should achieve thermal comfort of the interior spaces.*			
	Durability and maintainability (A2.4 = I2.2)	Maintainability (A2.4.2 =I2.2.2)	**AD-Norm = ID-Norm:** *Ease of access for cleaning the sun-shading panels and the glazing.*			
			ID-Norm: *The fixing design of the sun-shading panels should make the panels easy to be replaced individually without influencing other sunshades.*			
3. Economic	**Cost of service (A3.2)**	Cost of Energy (A3.2.1)	**AD-Norm:** *The design of building envelops should minimize cooling load of interior spaces.*			

Legend
- (grey bar) The continuity of the consideration for the norms proposed by the architectural design team
- (hatched bar) The continuity of the consideration for the norms proposed by the industrial design team

Table 11: Norms in design difference 3: connection design of the sun-shading panels

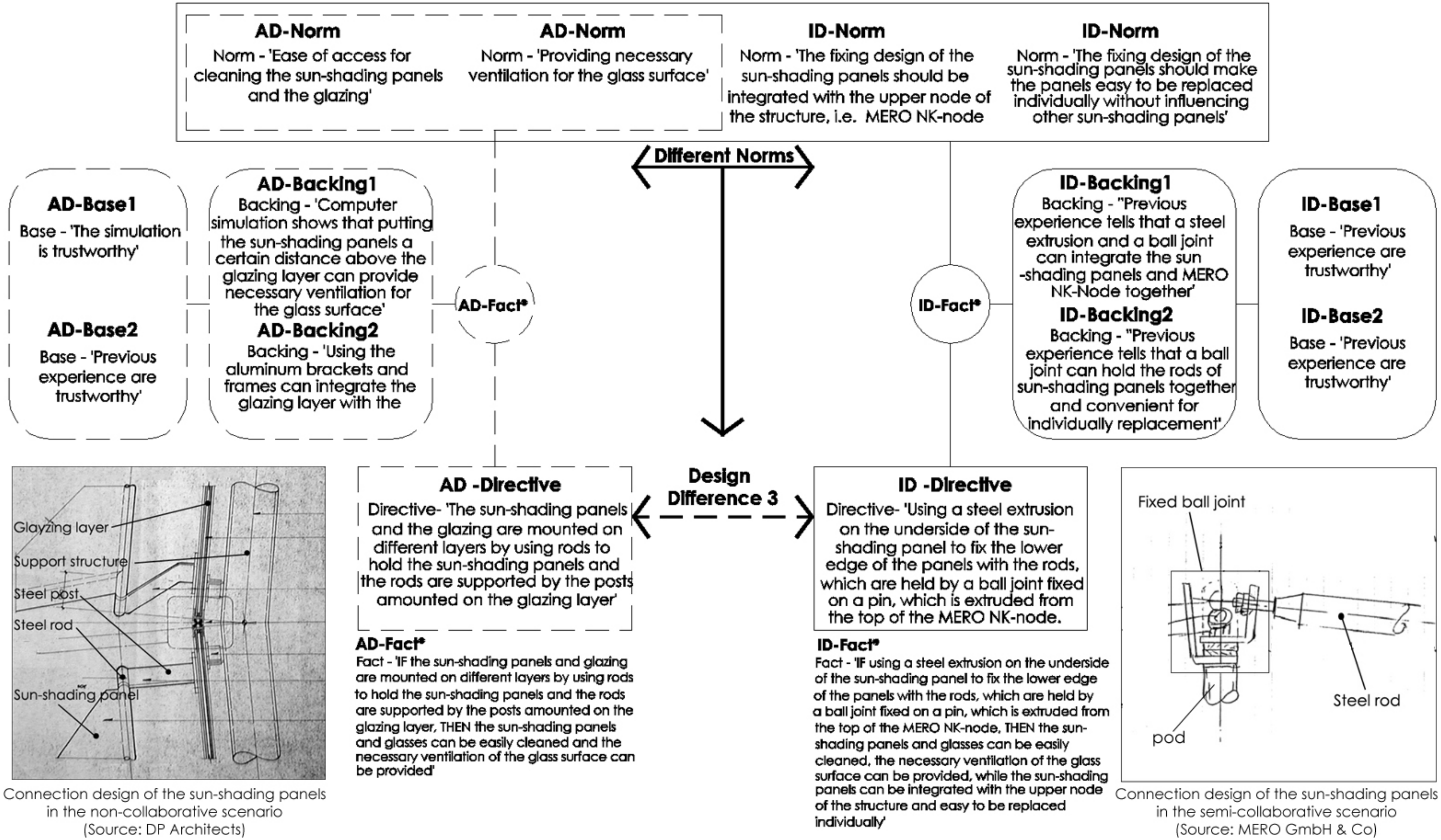


Figure 39: A diagram of design difference 3 (i.e. connection design of the sun-shading layer) formation

AD-Norm
Norm - 'Ease of access for cleaning the sun-shading panels and the glazing'

AD-Norm
Norm - 'Providing necessary ventilation for the glass surface'

ID-Norm
Norm - 'The appearance of the connection should be more elegant'

ID-Norm
Norm - 'The fixing design of the sun-shading panels should be integrated with the upper node of the structure, i.e. MERO NK-node

ID-Norm
Norm - 'The fixing design of the sun-shading panels should make the panels easy to be replaced individually without influencing other sun-shading panels'

AD-Base1
Base - 'The simulation is trustworthy'

AD-Base2
Base - 'The aesthetic statement is trustworthy'

AD-Backing1
Backing - 'Computer simulation shows that putting the sun-shading panels a certain distance above the glazing layer can provide necessary ventilation for the glass surface'

AD-Backing2
Backing - 'A smaller ball joint will be more elegant'

AD-Fact*

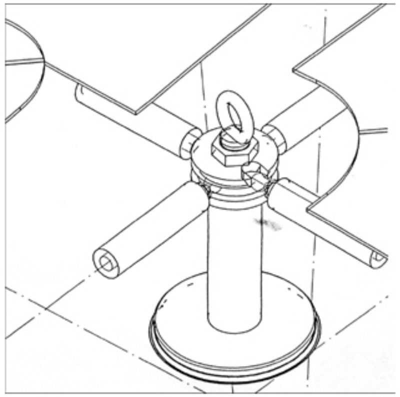
ID-Fact*

ID-Backing1
Backing - "Previous experience tells that a steel extrusion and a ball joint can integrate the sun -shading panels and MERO NK-Node together'

ID-Backing2
Backing - "Previous experience tells that a ball joint can hold the rods of sun-shading panels together and convenient for individually replacement'

ID-Base1
Base - 'Previous experience are trustworthy'

ID-Base2
Base - 'Previous experience are trustworthy'

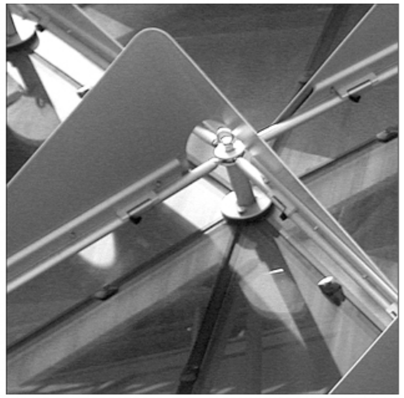


Connection design of the sun-shading panels in the full-collaborative scenario (Source: MERO GmbH & Co)

Collaborative Design -Directive
Directive- 'Using a steel extrusion on the underside of the sun-shading panel to fix the lower edge of the panels with the rods, which are held by an advanced ball joint system fixed on a pin, which is extruded from the top of the MERO NK-node'

AD-Fact*
Fact - 'IF a steel extrusion on the underside of the sun-shading panel to fix the lower edge of the panels with the rods, which are held by an advanced ball joint system fixed on a pin, which is extruded from the top of the MERO NK-node, THEN the sun-shading panels and glasses can be easily cleaned, necessary ventilation of the glass surface can be provided'

ID-Fact*
Fact - 'IF a steel extrusion on the underside of the sun-shading panel to fix the lower edge of the panels with the rods, which are held by an advanced ball joint system fixed on a pin, which is extruded from the top of the MERO NK-node, THEN the sun-shading panels can be integrated with the upper node of the structure and be replaced individually'



Connection of the sun-shading panels (Source: Author)

Figure 40: A diagram of connection design of the sun-shading panels in the full-collaborative scenario

4.3.2. Design difference 4: shape design of the sun-shading panels

In the non-collaborative scenario of the shape design of the sun-shading panels, DPA considers more about the visual effect that influences the overall effect of the roof cladding system. Beside the general norms about the entire sun-shading system, the norm of the gentle appearance of the sun-shading panels was stressed (see Table 12 in page 104). As a result, the directive, the panels are conically bent at the top, is generated.

While in the semi-collaborative scenario, MERO considered more about the norms of the feasibility of manufacturing the sun-shading panels in technical aspect and its ensuing issue in economic aspect. Because the cost of implementing the conically bent proposed by DPA is too high, MERO intentionally ignores the gentle appearance considered by DPA, which has conflict with the MERO economic concerns. Thus, MERO creates another new directive in this scenario, i.e. the panels are straight bent at the top (see Figure 41 in page 105).

It is notable that in the full-collaborative scenario MERO's directive was ruled out by DPA. For doing so, DPA resumed its initial norm on the appearance of the sun-shading panels since the straight bent at the top of the panels make those looks too aggressive. Thus a design conflict occurs. To solve the conflict induced by different norms from DPA and MERO, an acceptable directive, i.e. the panels are cylindrically bent at the top is developed (see Figure 42 in page 106). In this way, the manufacturing cost of the new solution is lower than that of the one proposed by DPA in the non-collaborative scenario and is higher than that of the one proposed by MERO in the semi-collaborative scenario.

While in the same way, the visual effect of the new solution is not as gentle as DPA's design, but much softer then MERO's alternative.

Design Constraint	**Description of Norms**			**Practice Process (Collaborative Scenarios)**		
				Non	**Semi**	**Full**
1. Aesthetic	**Views (A1.2)**		**AD-Norm:** *The design of the sun-shading layer should minimize the block of view outside.*	▒	▒	▒
	Exterior design images (A1.3 = I1.1)		**AD-Norm:** *The design of the sun-shading layer should create continuous visual effects for the sun-shading panels.*	▒	▒	▒
			AD-Norm: *The appearance of the sun-shading panels should not be aggressive.*	▒		▒
			ID-Norm: *The detail design of the sun-shading panels should minimize visual impact on sun-shading panels.*		▬	▬
2. Ergonomic	**Ambient environmental factors (A2.3)**	Indoor Thermal comfort (A2.3.6)	**AD-Norm:** *The design of building envelops should achieve thermal comfort of the interior spaces.*	▒	▒	▒
3. Economic	**Cost of service (A3.2)**	Cost of Energy (A3.2.1)	**AD-Norm:** *The design of building envelops should minimize cooling load of interior spaces.*	▒	▒	▒
	Cost of materials (I 3.1)		**ID-Norm:** *Reducing the cost of materials of the sun-shading panels.*		▬	▬
	Cost of manufacturing (I3.2)		**ID-Norm:** *The sun-shading panels should be easily manufactured.*		▬	▬
4. Technical	**Manufacturing (I4.2)**	Designing and operating the production system (I4.2.1)	**ID-Norm:** *The sun-shading panels should be easily manufactured.*		▬	▬
		Strength and stability (I4.2.3)	**ID-Norm = AD-Norm:** *The design of the sun-shading panels should achieve stiffness of sun-shading panels.*	▒	▒ ▬	▒ ▬

Legend
▒ The continuity of the consideration for the norms proposed by the architectural design team
▬ The continuity of the consideration for the norms proposed by the industrial design team

Table 12: Norms in design difference 4: shape design of the sun-shading panels

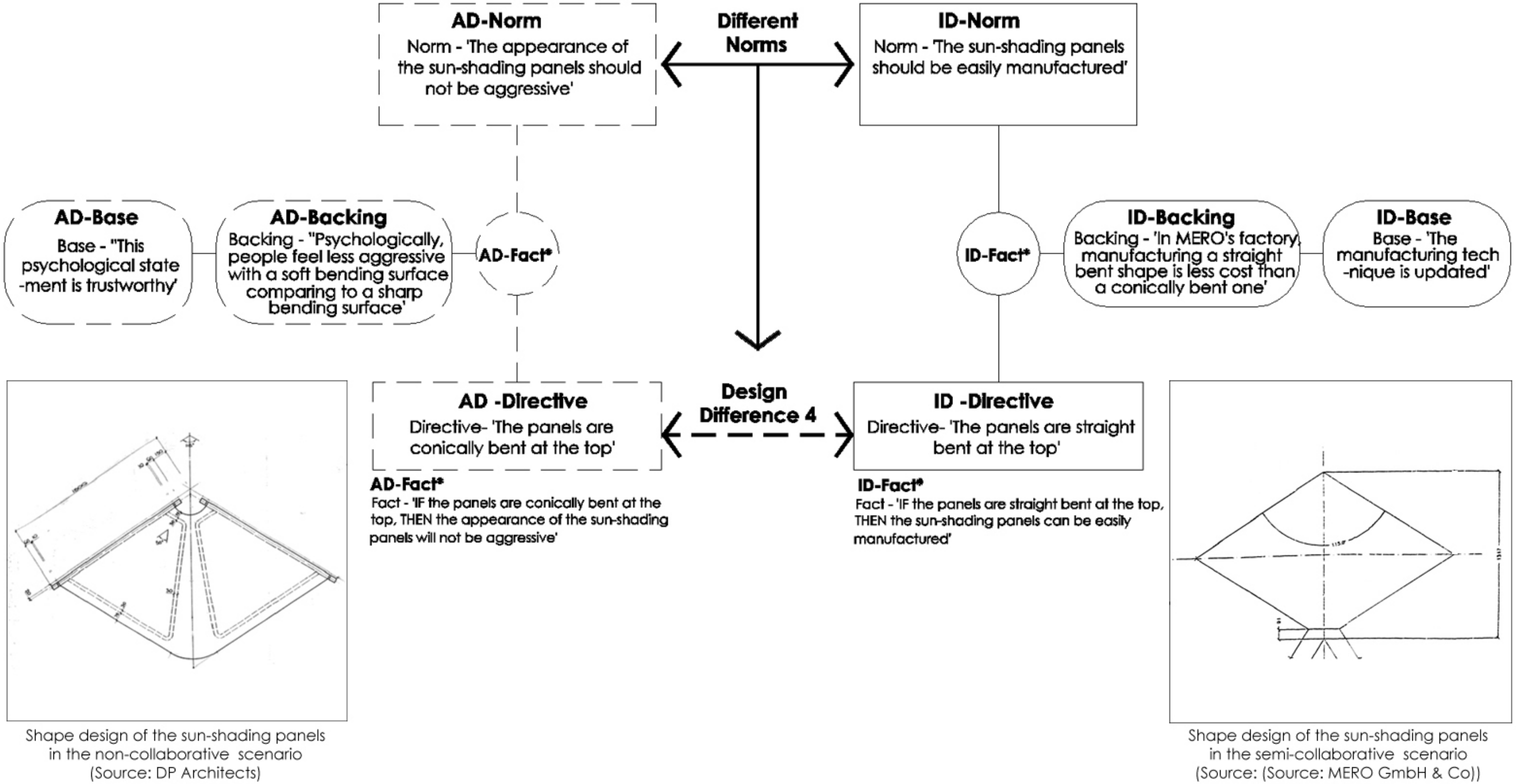


Figure 41: A diagram of design difference 4 (i.e. shape design of the sun-shading panels) formation

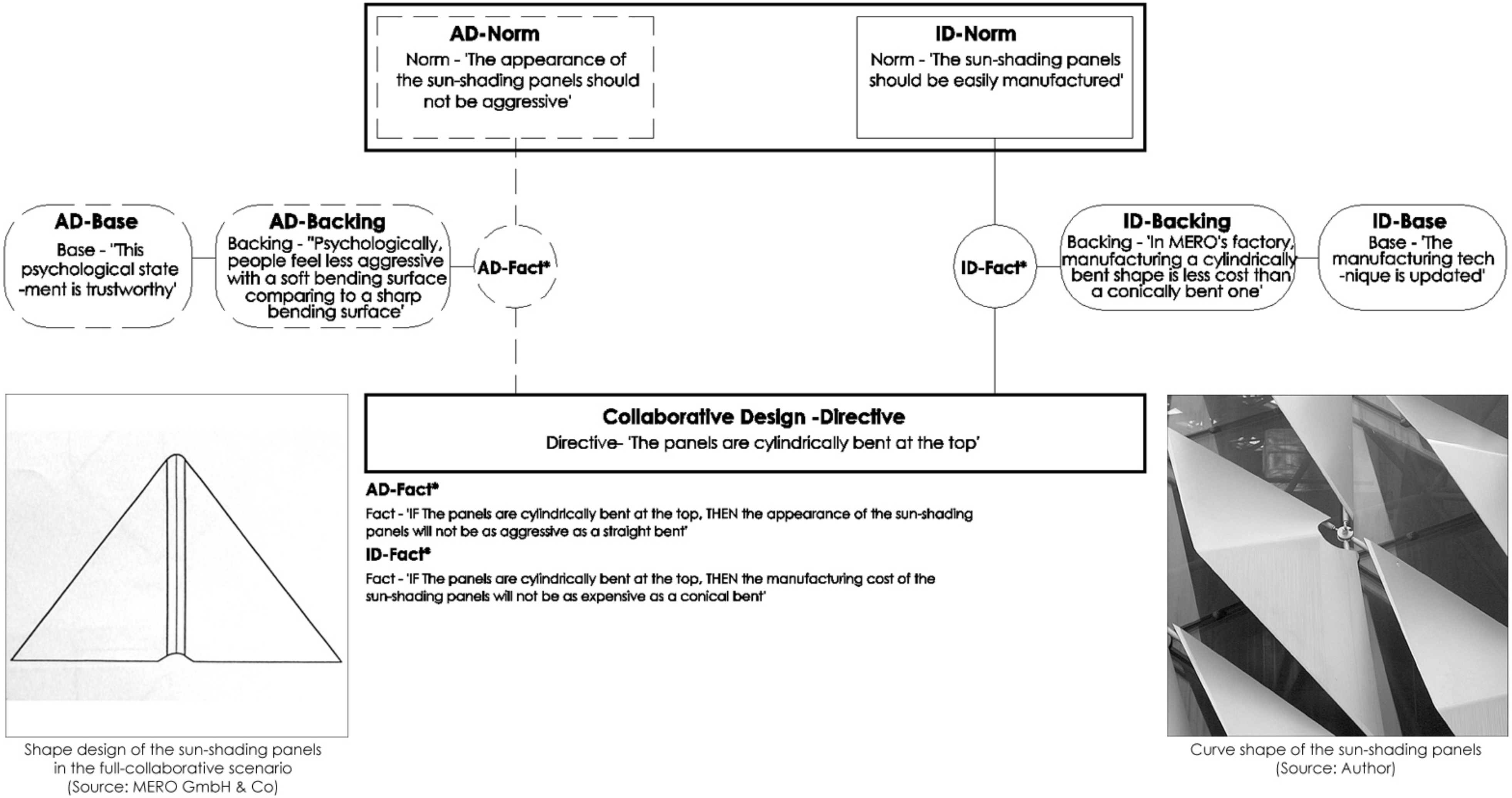


Figure 42: A diagram of shape design of the sun-shading panels in the full-collaborative scenario

	Design Difference Type	**Non-collaborative design process** (Non-collaborative scenario)	**Collaborative design process**		**Advantages of collaboration**
			Semi-collaborative scenario	Full-collaborative scenario	
Design difference 3: Connection design of the sun-shading panels	**Type I**	Using rods to hold the sun-shading panels. The rods are supported by posts amounted on the glazing layer.	Using a fixed ball joint to hold the rods, on which the sun-shading panels are fixed.	Using a ball joint system, with four rods fixed into one ball joint. And sun-shading panels are fixed on the rods.	**Quality** • The appearance of the connection is refreshingly of clarity. • Improvement in the fixing of sun-shading panels by allowing three degrees of freedom to each fixing point of the panels to follow up the complicated geometry of the building.
Design difference 4: Shape design of the sun-shading panels	**Type I**	The panels are conically bent at the top.	The panels are straight bent at the top.	The panels are cylindrically bent at the top	**Cost** • Decrease of cost due to the use of a cylindrically bent, which is cheaper in terms of manufacturing cost compared with a conically bent at the top of the sun-shading panels.

Table 13: Key design differences in development of the special products and advantages of collaboration

Design difference 3: Connection design of the sun-shading panels and Design difference 4: Shape design of the sun-shading panels

4.3.3. Advantage of collaboration: design difference 3&4

The final solution of connection design of the sun-shading panels, which integrated the considerations from both architectural and industrial design teams, allows three degrees of freedom to each fixing point. In this way, the panels can follow up the complicated geometry of the building while easy to be replaced individually. In addition, the appearance of the connection is elegant and refreshingly of clarity. In the shape design of the sun-shading panel, by using a cylindrically bent which is cheaper to be manufactured, the compromising solution reduced the manufacturing cost (see Table 13).

4.4. The implications

Based on the analysis of design differences in sections 4.2 & 4.3, a few implications can be made, which possibly facilitate the future collaboration between architectural and industrial design processes in customization of system products and development of special products.

Firstly, it is noticed that in the case study the customization process of applying structural system products to a specific building project generally includes two aspects. One is regarding the adaptation of the structural system products (the MERO space-frame structural system in the case study). It is a process for redesigning and optimizing the dimension and location of structural members to fit the overall particular geometrical form of the specific building. The other is to change and revise design of interfacial connection that conjoins the structural system products and the building envelop. Therefore, the application of structural system products leads to design differences at both overall design and detail design level, i.e. design difference 1: support structure design at an overall level and design difference 2: connection design of the glazing layer at a detail level. These design differences, according to the cause of their formation, fall into the category of Type II Design Differences, in which different beliefs of the architectural and industrial design team play a key role. As has been discussed in Type II Design Difference in chapter 2, the directives generated by a party with stronger backings usually have the priority over those generated by other parties. It is due to the fact that the directives from the former will mostly lead to a more reliable solution with the same design constraints such as those in aesthetic, ergonomic, economic, and technological aspects. As exemplified in the case study, in most situations of a collaborative design process industrial design teams possess the specialized knowledge of and rich experience in the application of structural system products in general. They are responsible for the further development of the products and have evident superiority over architectural design teams. As a result, when design differences arise in the semi-collaborative scenario, the directives generated by industrial design teams are almost unchallenged. These new directives usually can replace those generated in the non-collaborative design process by architectural design teams without inducing further differences and conflicts.

Secondly, it is noted that the design of special products involves more collaborative operations compared with that of system products. The design differences that arose in the design process of special products, according to the cause of their formation, fall into the category of Type I Design Difference, i.e. the difference between the directives generated by parties who have different norms for designing the same product (please refer to Chapter 2, p.42). For Type I Design Difference, two possible consequences can be induced. One is for the differences that arise between the directives generated by mutually exclusive norms, in which design conflicts occur and are solved with a compromising solution. This is the case with the design difference 4, i.e. shape design of the sun-shading panels in the case study. If the norms are not mutually exclusive but complementary instead, design difference will not lead to conflicts and can be integrated with an optimizing solution. This is the case with the design difference 3, i.e. connection design of the sun-shading layer in the case study. In each case, the solution is a result of collaborative directives generated according to both architectural and industrial design norms in a collaborative scenario (see Figure 43).

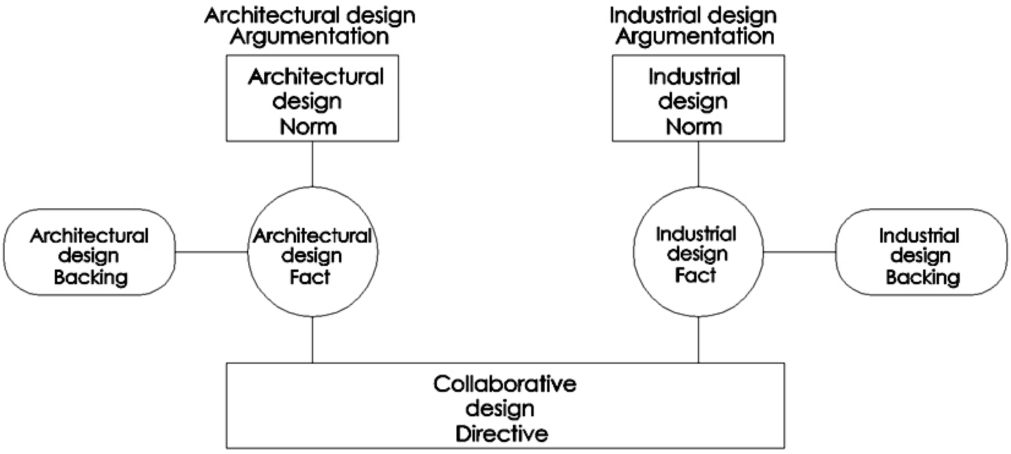


Figure 43: Type I Design difference solution in a collaborative design scenario

To facilitate detection and solution of Type I Design Difference, a machine-based framework, which is featured by surfacing design differences, will be useful to reinforce the collaborative design. The diagram below (see Figure 44) shows a possible framework for digital system and interface to describe the collaboration of architectural and industrial design processes. It includes a structure that maps the formation of the Type I Design Difference proposed in this study, which facilitates the interactions of these two parties on the design of special products in a parallel way in the full-collaborative scenario. Furthermore, it can also be used to assist the collaboration in both non-collaborative and semi-collaborative scenarios by providing a database which relies on precedent projects, which can be sorted according to the two types of design differences.

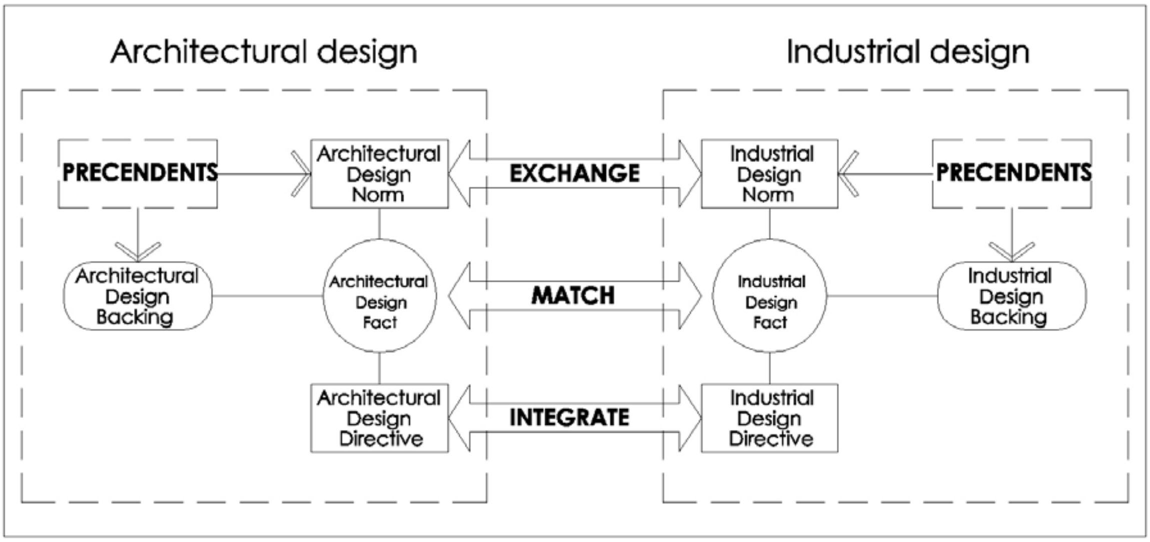


Figure 44: A framework for digital system and interface between an architectural design process and an industrial design process

Thirdly, an interesting comparison with three connection designs of the support structure, the glazing layer, and the sun-shading panels reveals how the application of the system product has an impact on its interfacial connection design. These three connections can respectively be seen as a standard system product, a customized system-product, and a special product. For the first one, the connection of the support structure retains the original connection design of MERO-KK node without any change in the customization process of the system product. For the second, the connection of the glazing layer undergoes a transformation from a separate component proposed in the original scheme by the architectural design team to a closely attached element of its adjacent node of support structure, i.e. MERO-NK node. Several necessary changes are made in response to specific requirements of the special geometrical form of the building. For the third, despite a few slight impacts upon it induced from the change of the support structure, the connection of the sun-shading panels basically remains as one independent component. This comparison implies that an introduction of structural system products will not only lead to the replacement of previous incompetent product design, but will, in a sense, change the nature of a related full tailor-made special product into a secondary system product. Arguably, in term of time and resource of design, both overall design and detail design will benefit from an early introduction of the structural system products.

4.5. Summary

This chapter has attempted to answer how the design differences arose in the collaborative design between architectural and industrial design processes in the case study. It was discussed in two categories. One is about design differences in customization processes of system products, i.e. the support structure and the glazing layer in this case. The other is about design differences in development process of special products, i.e. the sun-shading layer in this case. The structure and elements of the design difference formation were made explicit and how these key differences arose was analyzed. In addition, some implications for future collaboration were discussed and generated. For the system-product-related design difference, i.e. design difference 1&2 (i.e. structure design and connection design of the glazing layer), they arose mainly because to the same norm the architectural and the industrial design team had different backings and thus generate different directives. In other words, their knowledge and experience gave them different solutions to the same considerations. The design difference 3&4 (i.e. connection design of the sun-shading layer and shape design of the sun-shading panels), which are related to the specific products design, arose mainly because the architectural design team and the industrial design team emphasized on different norms.

Conclusion

Building project-related products include both system products and special products, the designs of which involve the collaboration between architectural and industrial design processes. The design differences arise in their collaboration influence the design quality. In order to understand design difference better and to facilitate seamless collaboration, this study has set out to establish a model of design differences in the collaborative design between architectural and industrial design processes based on a case study. To achieve this purpose, the following questions are formulated as highlightened in the introduction:

1. *What kinds of design differences can arise in the collaboration?*
2. *When do these design differences arise?*
3. *How do these design differences arise?*

Through answering these questions, the conclusion can be reached.

Above all, in terms of identifying design differences in the collaboration, two types of design differences are derived based on the *Kernel of Conceptual System* (Tzonis et al. 1978) and *structure of conflict* (Coombs and Avrunin 1988). They are:

> ***Type I Design Difference*** is a difference between the directives generated by parties who have different norms for designing the same product;
>
> ***Type II Design Difference*** is a difference between the directives generated by parties who have different backings to the same norms.

In the case study of Esplanade-Theatres on the Bay, four design differences are identified, which can fall into two types of project-related products, i.e. system products and special products (please refer to Table 4, Table 5, Table 6, and Table 7 in Chapter 3). In the customization of the system products, i.e. MERO space-frame structural system and its related glazing layer, Type II Design Difference is the salient difference arose in the collaborative design process, especially in the semi-collaborative scenario. While in the design of the special product, i.e. the sun-shading layer of the roof cladding system, Type I Design Difference is the salient one, which arises in both semi- and full-collaborative scenarios.

From this observation, two types of design differences demonstrate the distinctive roles played by products with different nature in the collaborative design of building project-related products. At the design thinking level, these design differences reflect different norms and beliefs of architectural and industrial design. In other words, the rise of these differences are linked with knowledge and experience of architectural and industrial design teams on the one hand, and with different constraints considered in architectural and industrial design processes on the other.

As for the question of “when do these design differences arise”, three design scenarios are identified in the case study, i.e. non-, semi-, and full-collaborative scenario. In the first one, the non-collaborative scenario, either an architectural design team or an industrial design team works alone without requirements for a specific project or product from each other. Usually, no direct design differences arise in a non-collaborative scenario between these two parties. However, some potential design differences may exist, which either will become explicit in the later stages of design or result in poor design if they remain implicit. The latter situation is especially notable on detail product design level. A semi-collaborative scenario starts when requirements from an architectural design team are forwarded to an industrial design team in form of tender documentation. In this scenario, despite less frequent interactive discussion between each other, the specific requirements regarding the product design from an architectural design team already impose constraints upon the design of an industrial design team. Thus design differences arise.

Such differences advance in two ways according to the nature of the products. For the system-product-related design differences, they usually arise only in semi-collaborative design scenario without any further design differences or conflicts in the full-collaborative scenario. It is due to the strong backings of industrial design team that architectural design team generally accepted the new solutions. For the special-product-related design differences, not only may they arise in semi-collaborative scenario, but some of them lead to further differences or conflicts that have to be integrated or resolved in the later scenario. In the full collaborative scenario, in which architectural and industrial design teams work together, two kinds of solution are drawn for special-product-related design differences. Some may be integrated to find an optimizing solution by combining the norms considered by both teams. And some can induce design conflicts, which need more intensive collaboration to find a compromising solution.

The Kernel of Conceptual System (Tzonis et al. 1978) is provided as an analytic framework to examine and evaluate materials in the case study for the central question "How do these design differences arise". It conceptualizes the design process with the key elements and structure for beliefs, judgment, and decision making. Insofar as the research topic concerns, a comparative study of architectural and industrial design thinking provides another part of the research framework. A general comparison between architectural and industrial design formulated their differentiation in nature of production, practice pattern, and design constraints, which represent the structure of design problem.

In the case study, four design differences are identified by comparing the explicitly mapped architectural and industrial design processes in the case study. The points of differences, levels of connections, and how they arise can be seen clearly. And how these design differences arise in the design processes is analyzed and discussed (please refer to Figure 35, Figure 38, Figure 39, and Figure 41; Chapter 4).

Based on these findings, some understandings of the collaborative design between architectural and industrial design processes are inferred and discussed. Firstly, the customization of structural system products for a specific building project can bring about design differences at both overall design and detail design level. These system-product-related design differences mainly fall into the category of Type II Design Difference, in which the directives generated by a party with more strong backings play a dominant role in the final solution for more reliable consequences brought by them. In the case study, the directives generated by an industrial design team, who has stronger authority than an architectural design team in terms of structural system products, are accepted by the latter without conflicts induced. It is suggested, therefore, that an architectural design team in a non-collaborative design process needs to identify and evaluate the possibility of application of system product. If the possibility exists, except defining the overall layout and providing requirements for related detail design, a detailed design from the architectural design team becomes less necessary. Instead, a specialized industrial design teams can be introduced to work in detail together with the architectural team. In other words, the semi-collaborative design scenario has to be moved up in the design schedule. In this way, time and cost can be saved in terms of the whole design process. To understand the norms behind the system product design helps architecture design teams leave more proper space for industrial design teams on the one hand. And the advancement of semi-collaborative scenario help industrial design teams timely understand the norms considered in architectural design processes on the other. This adjustment in a collaborative design process is of help in bridging the gaps between products and buildings and providing more flexible final system products.

Secondly, the design process of special products has a more complex collaborative mode than that of system products. The special-product-related design differences can largely fall into the category of Type I Design Difference, some of which may lead further to conflicts while others not. After making less valuable partial solutions from the non-through the semi-collaborative scenario, the final solution is reached in full collaborative scenario, in which the design process is distinctively characterized by exchanging norms considered by each party. In doing so, differences are integrated within an optimizing solution, and conflicts induced are solved within a compromising solution. Therefore, exchanging norms in the collaboration between architectural and industrial design teams plays a crucial role for both design teams in understanding each other's design. It is also indicated in the case study that, for a difference/conflict arising, an optimizing/compromising solution will only be reached in the full collaborative scenario.

Thus, moving into full-collaborative scenario earlier in the design process becomes an efficient way to help saving time and improving design quality. To facilitate the detection and solution of Type I Design Difference, a possible framework for digital system and interface to describe the collaboration of architectural and industrial design processes is proposed.

The results of this research attempts to shed light on the problems that exist for project-related product design with regard to the collaboration of architectural and industrial design processes. Increasing the general awareness of cognitive design differences should lead to a better understanding of collaborative design. Based on the model developed in this study, further machine-based models, which can facilitate collaborative design differences detection and solution, can be developed to facilitate practitioners in collaborative design, especially between architectural and industrial design processes.

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APPENDIX A

Illustrations of a specific project-related product

The followings are illustrations of the cladding system of Esplanade-Theatres on the Bay as discussed in the case study of a specific project-related product in Chapters 3 and 4.

General description:

Figure A- 1:

Site analysis (Source: DP Architects)

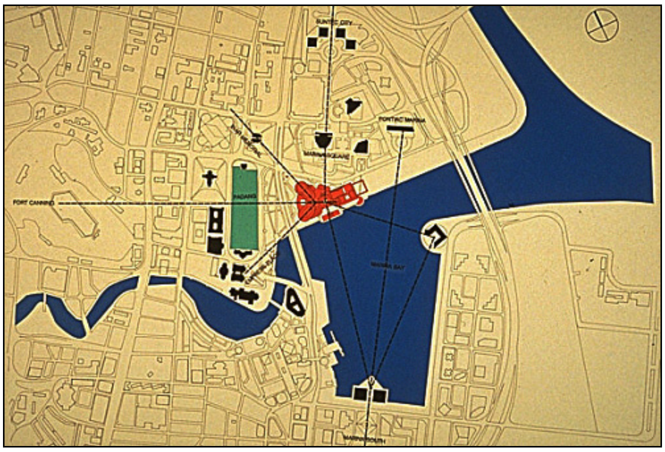

Figure A- 2:

Site plan (Source: DP Architects)

Figure A- 3:
Birdview of the site (Source: DP Architects)

Figure A- 4:
Exterior view of the roof cladding system (Source: Author)

Figure A- 5:

A prototype of the roof cladding system, which comprise three sets of key components, i.e. the support structure, the glazing layer, and the sun-shading layer (Source: DP Architects)

APPENDIX B

Design practice process of a specific project-related product

The followings are design information and design stages of the roof cladding system design of Esplanade-Theatres on the Bay as discussed in the case study of a specific project-related product in Chapters 3 and 4.

General information[36]:

Total Project Cost:	S$600 million
Projected floor area:	111.000 sq. m
Awards:	SIA-Bentley IT Awards—Top winner, Professional Category
Client:	Arts Centre Development Division of the PWD, acting for Ministry for Information and the Arts
Project Manager	PWD Consultants Pte Ltd
Architect:	DP Architects Pte Ltd / Michael Wilford and Associates (UK)[37]
Acoustic Consultant	Artec Consultants Inc (USA)
Theatre Planners/Consultants:	Theatre Project Consultants (UK)
Structural/ Civil/Mechanical Engineers:	PWD Corporation Pte Ltd
Cladding Consultant	Atelier One (UK)
Interior Design:	DP Architects Pte Ltd and DP Design Pte Ltd
Landscape Design:	ACLA Pte Ltd
Main Contractor:	Penta-Ocean Construction Co., Ltd (Japan)
Cladding Contractor:	Mero GmbH & Co. (Germany)

Table B- 1: General information of Esplanade-Theatres on the Bay

[36] These information are summarized based on following sources:
Esplanade Theatres On The Bay. *Asian building & Construction*. Sept/Oct 2000: 30-34.
Tan Hong Herng. 2002. Speaking volumes: crafting the esplanade. *Singapore Architect*, 214: 48-57.

[37] The formal contract was originally signed with this joint entity, though MWP are no longer part of the project since May 1995.

Key stages of project design development[38]:

The idea of a performing arts center was first floated some 20 years ago. However, it was in the 1980s that the idea picked up momentum.

- ***In 1987, the first functional design brief was completed with input from the arts community.***
- ***In 1989, the Government accepted the recommendation***39 ***of building a new arts centre in Singapore and the site was selected.***
- ***In 1990, a steering committee was formed to plan the project.***
- ***In 1991, a design competition was held and 48 applicants were involved.***
- ***In 1992, the Users' Advisory Group, Design and Aesthetics Advisory Group, and Commercial Advisory Group were formed.***
- ***On 26 September 1992, the Singapore Arts Centre Co was established to lead the project. By December, the key members of the design team were in place.***

  The design team then includes: the theatre planners Theatre Project Consultants (UK), the acousticians Artec Consultants (USA), and the architectural team of DP Architects (Singapore) and Michael Wilford and Partners (UK). The Public Works Department was to be in charge of project management, quantity surveying and engineering services.

- ***In 1993, to facilitate dialogue among the key players of the project, a Panel of Asian Experts was appointed.***

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[38] It is summarized based on the information from following sources:
Author's interview with Mr. Vikas M. Gore
The Esplanade Co Ltd Annual Reports
The Esplanade Co Ltd. 2002. *Opening esplanade theatres on the bay.* Singapore: The Esplanade Co Ltd.

[39] The recommendation is from the Advisory Council on Culture and the Arts, chaired by the then Deputy Prime Minister Ong Teng Cheong.

- ***In November 1993, the master plan was finalized.***
- ***On 21 July 1994, the scheme was shown to the public in an exhibition "Taking Shape"***

By then architects had not really decided what kind of treatment the cladding would have (See Figure B-1). And many comments from the public were received. "Debate raged over the original schematic design. It was deemed 'ugly', 'un-Asian' and 'uninspiring' by some. While it was acknowledged as well-planned, there was a concern that functional needs tool – priority over form. Whereas others felt that it was 'genuine attempt to discover new forms', the two elongated domes were considered too dominant and monolithic, and as such, relegated the outdoor needs of Asian arts to the sidelines. Yet another view likened the domes favorably to 'papayas' and saw them as the only feature that felt Asian. They were also thought of as 'concrete blobs'. This was in fact a misconception; as the model then had not taken into account the materials and textures for its exterior." (The Esplanade Co Ltd. 2002, 18) The architects felt that these comments needed a response.

Figure B- 1: The Layout of 1994 Scheme (source: DP Architects)

- ***Late 1994: Some alternatives of the change in geometry were compared.***

One idea was that there will be trusses from the bottom edge to the top edge, with smaller trusses side to side and sunshades mounded above them. Another option was having just vertical supports with sunshades in between that would get smaller as they go to the top. But the design and fabrication was coming very difficult for that option.

- ***In May 1995, Michael Wilford & Partner, who worked on the project with DPA, withdrew from the project.***

DPA continued work with Atelier one – an engineering firm based in London—on the cladding system.

- ***In 1995 -1996, the new idea of 'the equal length link mesh' was come up with.***

The geometry of this scheme can be illustrated by a kitchen sieve (see Figure B-2) reshaped on the volumes of the two cladding shells (see Figure B-3). The problem of using this scheme is that it is almost impossible to design if you do not use computers. Without computer it would be extremely complex. If using computers, the mesh can be laid over a curved surface, and capture the geometry quite easily. Since Michael Wilford & Partners, who worked mainly on paper rather than on computers, were no longer on the project, there were no problems of using computers between DPA and Atelier One.

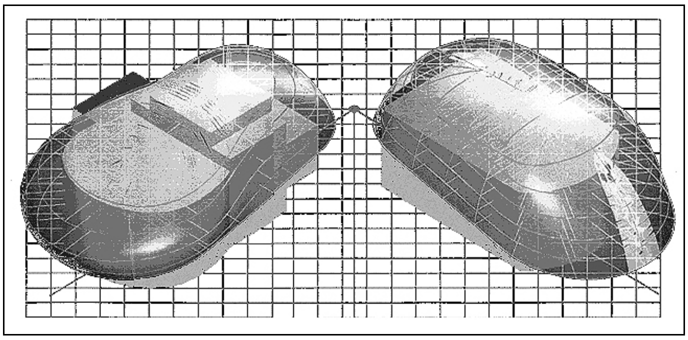

Figure B- 2: Volumes of Lyric Theatre and Concert Hall (source: DP Architects)

Figure B- 3: An example of an equal length link mesh (source: DP Architects)

- ***In 1996, the first tender was called for the cladding system.***

  The procurement of the roof cladding system adopted a two-stage tender approach. In the first tender stage, which was called for the design and built of the cladding system, about five contractors competed. MERO had an alternative proposal, which turned out to be the cheapest option that complied with all other requirements.

- ***On August 11, 1996 Deputy Prime Minister Dr. Tony Tan marked the start of construction through a ground breaking ceremony.***
- ***From 1996 to 1997 is the design development period, during which DP architects and MERP worked together.***
- ***In 1997, the main contract tender was called.***
- ***June 1997, the cladding tender was awarded to Germany-based Mero-Raumstruktur GmbH & Co.***
- ***1998: The substructure was completed followed closely by the start of construction of the superstructure above ground.***
- ***February 2001: the superstructure was completed***
- ***October 12, 2002: Esplanade - Theatres on the Bay opened her doors to the world***

APPENDIX C

Discussions between the author and Mr. Vikas M Gore of DP Architects

The following are abstracts from author's interview (in Feb 2002) with Mr. Vikas M Gore, the project director and a director of DP Architects, for the design of the roof cladding system of Esplanade project to explore the collaborative design process between DPA and MERO.

AUTHOR: who are the main parties that were involved in the design process of the roof cladding system?

MR. GORE: There were three main parties involved, one was DPA. Atelier one is an engineering firm based in London, whom DPA hired to work with us on this project, not on the whole project, but just on the cladding. And of course MERO, the contractor. A lot of industrial design and detail design was done in-house by MERO.

AUTHOR: What are the major changes in terms of the roof cladding system design?

MR. GORE: In the middle of 1995, Michael Wilford & Partner (MWP) withdrew from the project. And at that time, MWP worked mainly on paper other than with computers, while DPA was quite deeply involved in 3D modeling in computer as you know. So the withdraw of MWP gave us some freedom to design and to apply more of our knowledge of computers. Before Michael Wilford & Partner withdraw from the project, they actually introduced an engineering firm to us called Atelier one, who are based in London. And as it happened, Atelier one used the same software as DPA. Therefore we can exchange data with them directly and fluently.

We have to meet three main criterions. Firstly, we had to air-condition the foyers, because in Singapore everybody expects the air-conditioning. And secondly, we wanted to have views out, because on one side it is the bay and on the other side it is the city district and the Raffle city. Almost all directions of the site have very good views. And thirdly, we do not allow more direct sun coming in, because it will make air-conditioning too expensive and people will not be comfortable even with air-conditioning. So we came up with this idea of what we call ‘the equal length link mesh’. The kitchen sieve is a good illustration of how the geometry works. With that idea, we can get many different types sunshades with very few shapes. Also, we can get many different ways to prevent from the sun. So we found that we can strive for good compromise between achieving views of the scene people want to see and yet protecting the inside from the sun.

The other big change actually came when MERO came on board. Because up to that point, our structure was a single tube structure, single layer, it was supposed that the tubes will be about 62 inch in diameter. And there will be variation on the junctions. But MERO changed it in the tender.

The way MERO being selected was an open tender, and about 4 or 5 manufacturers competed for it. MERO had an alternative proposal which turned out to be the cheapest tender. It also complied with all our other requirements. In this alternative proposal, instead of using a single tube, it uses a space frame structure. MERO is one of the early pioneers of using those horizontal three-dimensional space-frames; however they were usually flat ones. But with the use of computers, they know that it is possible to modify it into a curve shape or a dome shape. And we like this alternative because instead of using steel tubes that were 62 inch in diameter, now we can use steel tubes about 50mm in diameter. When you look at the shell from inside, that has a major impact on the design. It is more like a least kind of experience rather than heavy grid experience. Therefore we decided to accept the alternative proposal.

The space frame structure is a prefabricated product, which can be modified and used for different applications. They adopt steel members on the space frame. Instead of being round, the section of the steel members is a square. The advantage of the square section is that we can put a gaskin directly on it and put the glass directly on the top edge of the space frame.

AUTHOR: when was the tender of the cladding system held?

MR. GORE: The tender was held in 1996, it was a long time before the main contract tender was called, mainly because we need the finial design for the cladding so that we can determine its weight and so on. And we realized that in terms of design, this was the most complicated part. So actually the tender of the cladding shells was called long before the main contract was call in 1997.

AUTHOR: So after the tender, DPA worked together with MERO on the design of the cladding system?

MR. GORE: Yeah. But after MERO was involved, the new initiatives for changes of design all came from MERO other than us. Because once a contractor is involved in, it becomes a formal contractor situation. But we either accept or reject their proposals and ask for more modification. Between 1996 and 1997, it was design development period, on which DP architects, Atelier one and MERO were working together. It was a kind of back and forth things, what at finally results in design.

AUTHOR: What kind of suggestions did manufacturer and designers provide?

MR. GORE: When they initially proposed a space frame solution, the motivation was building fabrication. Because using the space frame, even in a project as highly customized as this, they can make the fabrication very easy. Because they have computer-driven machines in their factory, which can fabricate these components very fast once the design is complete. Whereas if it was done by welding tubes on site, it will have a longer period and much messier situation on site. Our motivations in accepting it lied in two aspects. One is that if it makes the cost cheaper, so the contractor's offer would be cheaper. The other is that we feel that it added a lot to the design.

When we saw the alternative we realize that it has a lot of potentials. Certainly we also realized that because it was going to be made in a factory as prefabricated components, it will be much easier to control. If everything is fabricated in a factory and assembled on site, the chances of going wrong will be less.

APPENDIX D

Discussions between the author and Mr. Claus Kaspar of MERO GmbH & Co

The following are abstracts from correspondences (from 2002 to 2003) with Mr. Claus Kaspar, the project manager of MERO GmbH & Co, for the design of roof cladding system of Esplanade-Theatres on the Bay to confirm and expand various understandings already established by interview and from other sources:

1.

"Li Suping" wrote:

1) Could you briefly introduce the design team of MERO in the Esplanade project? Their training backgrounds and responsibilities in this project?
2) Why die MERO adopt a space-frame structure instead of the single tube structure proposed by architects?
3) With regard to the detail design, such as the upper node of the space frame, have they been used in other projects previously and just adjusted to fit this project? Or are they specifically designed for this project?

"Claus Kaspar" replied:

Please find below a short reply regarding your questions as received recently (- I hope it's not yet too late):

To 1) Design Team:

a) Mr. Dr. Herbert Klimke (Technical Director - Design Development)

b) Mr. Dr. Jaime Sanchez (Architectural Engineering - Design Development and Geometry)

c) Mr. Mihail Vasiliu (Structural Engineer Steel & Concrete Structure)

d) Ms. Förster+Sennewald GmbH Munich (Structural Engineers Concrete Structure (Lower Gutter Beam & V-Columns)

e) Mr. Wolfgang Stühler (Design engineer, team leader)

f) Mr. Köhler (CAD-Engineer)

Mr. Beck-Hippeli (CAD-Engineer)

Mr. Burckart (CAD-Engineer)

g) Mr. Paul Kraus (Space Frame Design)

Mr. Günther Dürr (Space Frame Design)

h) 2 - 8 CAD draughtsmen

To 2) Reasons for a Space Frame structure:

a) High structural effectiveness compared to the amount/ quantity of steel required;

b) High flexibility in terms of varying geometrical and structural conditions and requirements;

c) Extremely low manufacturing tolerances;

d) High accuracy of the steel components thus facilitating the installation significantly;

e) A fast and comparatively easy installation with a high accuracy;

f) Reduced requirements for the scaffolding required;

g) Reduced requirements in terms of transport;

h) No welding on site (incl. all the required tests) required;

i) Commercial aspects;

j) Traditional Mero product;

To 3) The Space Frame system has been used in a very similar way on numerous other projects before. However, some aspects have been modified/ revised in order to meet the specific requirements of the Architects on this project (e.g. the fixing/ connection to the shading elements). But e.g. the aluminum shading panels and roof panels with all the associated details have been developed specifically for this job only.

2.

"Li Suping" wrote:

I attached below three design differences between DPA and MERO (the architectural design team and product design team) in terms of the roof cladding system design. If possible, would you like to have a look? Please kindly point out anything inappropriate. Your any comment and suggestion is welcome.

Design differences between architect and manufacturer

The roof cladding system design of the Esplanade project

Difference 1: structure design of the cladding system

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

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

Manufacturer-designer:	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.
Architect:	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-designer:	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 joint is loosed, all the four sunshades connected to this point will become loose.
Final design:	A ball joint system, with four rods fixed into one ball joint. And sunshades are fixed on the rods.

Difference 3: Detail design of the sun-shading panels

Manufacturer-designer:	the folding line of sun-shading panels should be a right angle, so they could be manufactured easily
Architect:	It should be a curve angle, so it will not look so aggressive.
Final design:	Using a curve angle for the folding line

"Claus Kaspar" replied:

Please find some short answers implemented below.

[About design difference 2]

The original proposal was rather complicated and cost/time-intensive taking into account that the design parameters (size; length; angles) are varying with every panel. It is further not confirmed that the dimensions given in the original proposal for the fixing of the sunshade panels would have been sufficient to comply with the architects/PWD's requirements regarding:

a) the original wind loads as stated in the specifications;

b) the live loads for the system (PWD/DPA additionally introduced the requirement that the fixing system/main colts have to serve as fixing points for cleaning staff and withstand the impact of the to be expected loads).

These requirements had to be considered and, of course found their reflection in the size/dimensioning of the material.

At the same time it was required to develop a feasible system/design which would react flexible on the changing geometry of the building and thus facilitate the manufacturing process and the installation. The development of a fixing detail with a repetitive nature further complied with PWS's request to reduce the cost for the building.

Please note that it is not required to open up/loose the ball joint fixing in order to replace a sunshade panel. Each panel is provided with 4 hinges which easily can be opened up in case it should be required to replace a panel.

3.

"Li Suping" wrote:

Regarding the design of the roof cladding system of the Esplanade project, could you please provide some information to the questions below?

1) May I know the figures of the final cost of MERO's option and the estimated cost of DPA's original scheme?

2) With regard to the construction time of the roof cladding system, may I know how much time is saved finally by MERO's option compared with the estimated construction time of DPA's original scheme? How long does it actually take for the construction of the support structure, the glazing layer and the sun-shading layer respectively?

“Claus Kaspar” replied:

To 1.) Unfortunately I'm not in position to give you the figures for MERO's actual costs for their works (company internals). The amount estimated initially by DPA for their original concept has not been made known to us (but I' m sure that the original cost estimation, realistic or not, indicated a figure which was less than the one for which MERO finally has been contracted to carry out the works). However, of more significance might be a comparison of the costs between the option offer by MERO and the realistic costs of the option originally planned by DPA. Certainly the largest savings, direct and indirect have been achieved by using/ accepting MERO's proposal for the Space Frame structure. Due to the highly material/ cost/ structural capability efficiency, the simplified and highly acurate installation, the reduced construction time and the associated savings in connection with the required scaffolding for the erection (access and propping) I would reckon that the saving should not be less than a 7 figure S$ amount.

To 2.) To complete the works for each individual building took approx. 8 months, in total we had a net construction period of 11 months with Concert Hall starting in March 2001 and finishing with Lyric Theatre in January 2002. If I' m not wrong the initial construction programme indicated a total installation period of 14 months for both buildings. If we could have circumnavigated some disturbing external factors (interruptions by the main-contractor, provision of scaffolding in time, delivery of material by suppliers) the construction period could have been reduced further.