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ADAPTING ADVANCED ENGINEERING DESIGN APPROACHES TO BUILDING DESIGN – POTENTIAL BENEFITS

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ABSTRACT: A number of industries continuously progress advancing their design approaches based on the changing market constraints. Examples such as car, ship and airplane manufacturing industries utilize process setups and techniques, that differ significantly from the processes and techniques used by the traditional building industry. One important difference between the building and other industries is that no prototypes are trialed and tested before manufacturing. This fact causes the design stages to be highly iterative without implementing prototype performance data into the global design process. Evolutionary design i.e. is one technique that aims to adapt the biologic process of evolution to engineering. This technique could have the potential benefit of reducing the design iteration from concept creation to construction. The paper identifies possible differences between the industries and the analysis of the benefits from adapting Evolutionary design to concept creation, evaluation and optimization based on building performance criteria. This paper summarizes the latest research findings documented in subject related literature. Furthermore the iterative character of building design will be detailed by stating key results from design team observations. The final conclusions will indicate reasons why techniques as evolutionary design were not yet successfully integrated to building design.

Keywords: Building design process, Design spiral, Evolutionary computing, Point to point design, Set based design,

1. INTRODUCTION

When stripped down to its basics a parallel can be drawn between industries designing and manufacturing cars, ships, airplanes and buildings. Their basic commonality is to manufacture a product which complies with the client's expectations and requirements.

Whilst the functions the end - products have to fulfill differ significantly, the techniques applied to find solutions to the stated design problem show similarities.

Exemplary, a building need to fulfill the following minimum functions depending on its proposed use: provide a place to shelter, celebrate, work or worship, and withstand the forces of nature.

A ship needs to keep the water outside, float upright in water, steer straight, have some mechanism for propulsion, accommodate crew and passengers, and allow for storing everything that must go aboard.

Cars need to move forward when driven, allow for changing the direction, and accommodate diver, potential passengers and everything that needs to be taken.

Airplanes need to be able to maintain its structural integrity when being driven through air, accommodate crew and passengers allow for storing everything that needs to go aboard and have elements present that stabilize and control the angle of motion.

In order to enhance the product efficiency and to minimize the design effort,
processes have been formulated consisting of a number of sequences. One feature, common to all industries listed, is the identification of the design requirements as a first step and making the product available to the client as the last step. In between those corner stones the processes used vary significantly across industries.

Whilst the building and airplane industry use point to point design processes, the ship manufacturing industry uses a spiral design process and one rather unconventional scheme is used by the car industry which is referred to as set based design.

The main differences can be identified when considering the number and purpose of design sequences and the consideration of design iterations.

By reflecting on the practical integration of concept optimization in other industries the paper aims to identify potential benefits to building design, where it is rarely used.

2. METHODOLOGY

The work presented is a result of a number of research activities such as literature review and design team observations.

During the review of subject related literature the authors considered literature used for educational purposes, when limited knowledge was available as in domains like car, ship and airplane design.

The focus of the review lay on identifying commonalities and differences between design process schemes and the latest techniques used or proposed to enhance the design process efficiency.

The second scientific measure was the observation of one building design team meeting. As one meeting is not representative to understand the design process used by an entire industry more are planned for the future. As this research is an ongoing process the section usually titled conclusion has been titled preliminary conclusion.

A third measure used was conducting interview with 15 international building design practitioners to gain knowledge about the current design practice.

3. BRIEF BUILDING SYSTEM DESIGN HISTORY

It is common knowledge that the need for shelter against the climate conditions is as old as the human species. However the level of quality for planning and erecting structures to work, live, celebrate or worship changed dramatically over the centuries accommodating issues as hygiene, safety, thermal comfort etc.

Considering thermal comfort in more detail, until the industrial revolution passive measures as overhangs, natural cross ventilation etc. were the only means to cool spaces providing comfortable internal conditions and therefore integrated into the design. Electric power, first available in the late nineteenth century, enabled the move towards mechanically assisted means of conditioning spaces. This technology was understood as a great opportunity by building designers to overcome the traditional restrictions set by the ambient conditions. Subsequently, every design became feasible separating the design effort to achieve appropriate form, function and comfort. Independent of the regional climate i.e. large areas of façade glazing at each orientation, lightweight building constructions, deep plan buildings etc. were considered possible design solutions.

The development was brought to abrupt hold with the energy crisis in the early 70`s. The energy consumption of buildings was suddenly considered a huge potential to reduce the economies primary energy demand. The need to reduce the energy consumption caused the building industry to reconsider its design approach away from disintegrated designs using fully mechanical systems towards combinations of passive and mechanical systems forming partly integrated design solutions.

As part of the development the strict hierarchy between design team members had to be broken up to give way to more flexible design procedures and to allow for performance based rather then prescriptive design.

4. DESIGN PROCESS

In theory, the design process describes a series of actions and/or operations undertaken to solve a design problem. In consideration of the perspective chosen for this research it typically results in the manufacturing of a product, which could, in the context of this paper, be a car, ship, airplane or building.

The process is typically structured forming a procedure with a start and finish to complete the design task. Its structured character enables to sequentially collect and produce design information as an aid for making design decisions. (Lamb, 2004)

The sequences or design stages making up the design process depend on the end - product. The processes described below differ in the number and purpose of the design stages and the integration of design iterations.

4.1 Building construction– Point to point design process

Simplified, the building design process, as appoint to point approach, comprises of. A number of seven important design stages as indicated in table 1. The process is of rather generic character with design iterations taking place in between the design stages depending on the appropriateness of potential design solutions towards the client's expectations and design brief.

Figure 1 below shows two flowcharts, firstly the design stages and secondly, separated from the first, potential design iterations. Design iterations have the potential to increase the building costs and should therefore best being avoided.

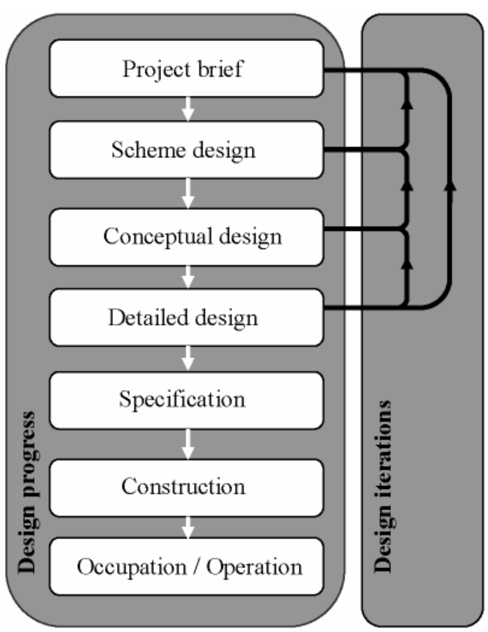

Figure 1, Building construction – Point to point design

When interviewing international design professionals it was stated that they experienced the design process a rigid and inflexible. Other comments dedicated to the conceptual design stage was that design optional are discarded to early to truly understand their benefits leading to local optima's rather than global optima's.

Table 1, Building design stages (RIBA)

Pos.	Design stage	Explanation
1	Project brief	Definition of objectives and requirements
2	Scheme design	Feasibility check of different options
3	Conceptual design	Main system selection concept development
4	Detailed design	Development and integration of design elements to provide build and operate design solution
5	Specification	Production of site drawings, product specification and construction resource documentation
6	Construction	Translation of design documentation into finished product, testing and commissioning
7	Occupation	Product handover, Design participants performance evaluation

4.2 Ship design – Design spiral

The ship design process shows commonalities and differences when compared with building design. Whilst the order of the traditional process stages compare nicely with the building design process: Design statement, first; concept design, second; preliminary design, third; and detailed design, last; the integration if design iterations differs significantly.

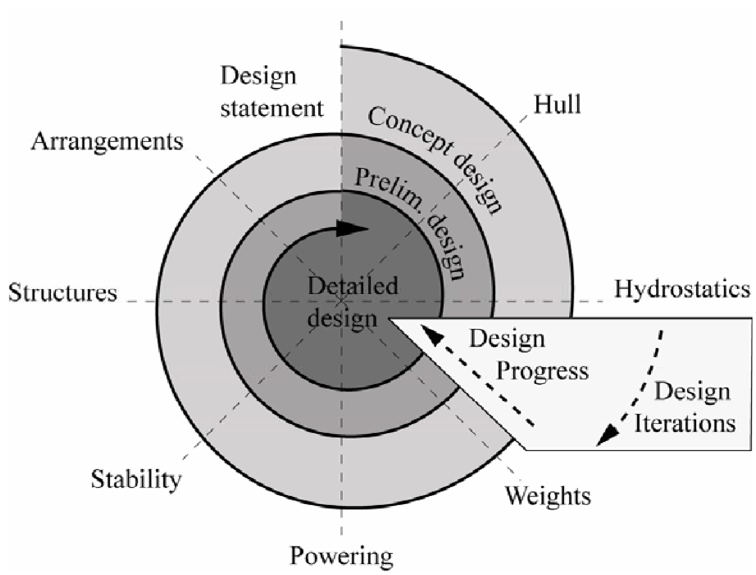

Figure 2, Ship design process – Design spiral

Figure 2, indicates that design iteration are considered part of the design process as each design element as hull definition, hydrostatics etc. are revisited at each design stage. The success of the performance based design is evaluated using a measure of merit starting at the very early design stages. Typically design optimization is used already during concept design as trade offs between the design elements influence the ships final performance.

Table 2, Ship design stages (Hollister, 1994)

Pos.	Design stage	Explanation
1	Design statement	Purpose and mission of vessel, owner requirements, definition of measure of merit, design constraints
2	Concept design	Feasibility check of design options, option optimization
3	Preliminary design	Calculation and trade off evaluation of hull shape, arrangements, weight, structure and performance prediction
4	Detailed design	Production of workshop drawings, product specification and templates
5	Construction	Translation of design documentation into finished product and testing
6	Delivery	Product handover

4.3 Airplane design – Point to point design process

The airplane design is referred to as a highly iterative process. Once the requirements have been established a specification is drawn up leading straight into the conceptual design stage. Even so the design process is sketched as a point to point flow chart the stages conceptual, preliminary and detailed design involves many different design disciplines one relying on the output of the other.

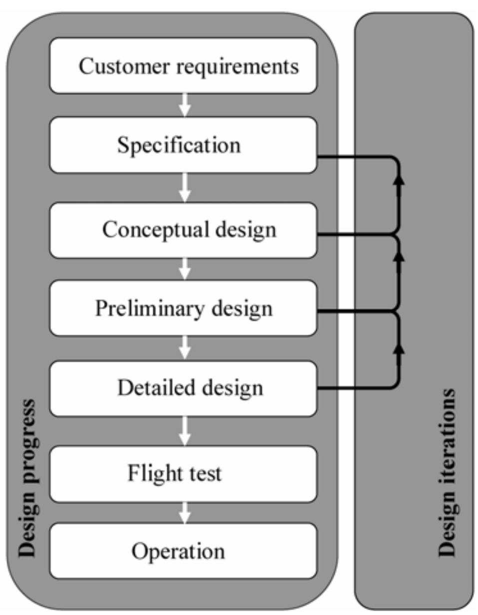

Figure 3, Airplane design process – Point to point

The results of the first prototype manufactured during the detailed design stage are fed back into the design as part of the product optimization approach. Multidisciplinary optimization techniques are used during the conceptual and preliminary design stage where different design options are considered and worked out in more detail. (Antoine and Kroo, 2004)

Table 3, Airplane design stages

Pos.	**Design stage**	**Explanation**
1	Customer requirements	Statement of intend.
2	Specification	Production of design requirements based on market/operation analysis research and most importantly customer requirements.
3	Conceptual design	Main system selection concept development and evaluation.
4	Preliminary design	Development and integration of design elements to provide build and operate design solution.
5	Detailed design	Production of workshop drawings, product specification, construction resource documentation. Results: Construction Authorization and First Prototype.
6	Flight test	Extensive product testing and certification.
7	Operation	Product delivery, maintenance and support.

4.4 Car design– Point to point design process

The traditional car design process is usually sketched the same way as for buildings and airplanes using a point to point flow chart.

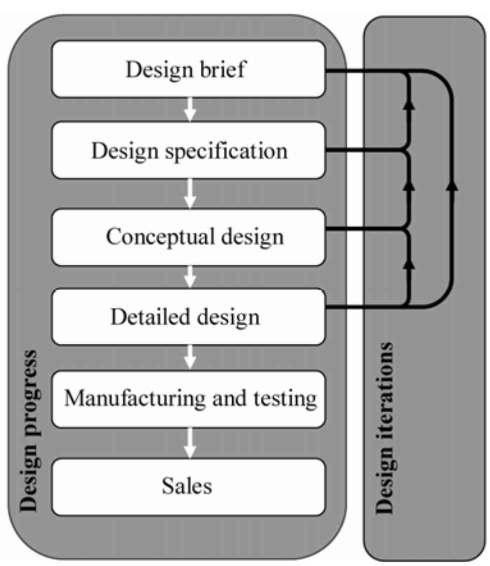

Figure 4.1, Traditional car design process – Point to point

However as it is true for the airplane design, design iteration can not be avoided and are accounted for. Figure 4.1 indicates design stages already known from processes used for the design of buildings, ships and airplanes: conceptual design and detailed design. As can be noticed the design stage called preliminary design is missing. However, the tasks previously accommodated in the preliminary design stage have been distributed across conceptual and detailed design. Prototypes are tested during the detailed design stage and the results are fed back into the design for system integration evaluation and optimization.

Table 4, Car design stages

Pos.	**Design stage**	**Explanation**
1	Design brief	Statement of intent to design and manufacture a specific vehicle.
2	Product design specification	List of design requirements containing results from customer market surveys and competing products analysis.
3	Conceptual design	Concept generation and evaluation by brainstorming and matrix evaluation. Result: Outline of design proposal.
4	Detailed design	Production of manufacturing drawings, product specification and prototypes to test system integration.
5	Testing and manufacturing	Extensive product testing for certification and manufacturing
6	Sales	Market introduction

4.5 Car design– Set based design process

The set based design accredited to Toyota comprises of the same design stages as other industries concept, preliminary and detailed design.

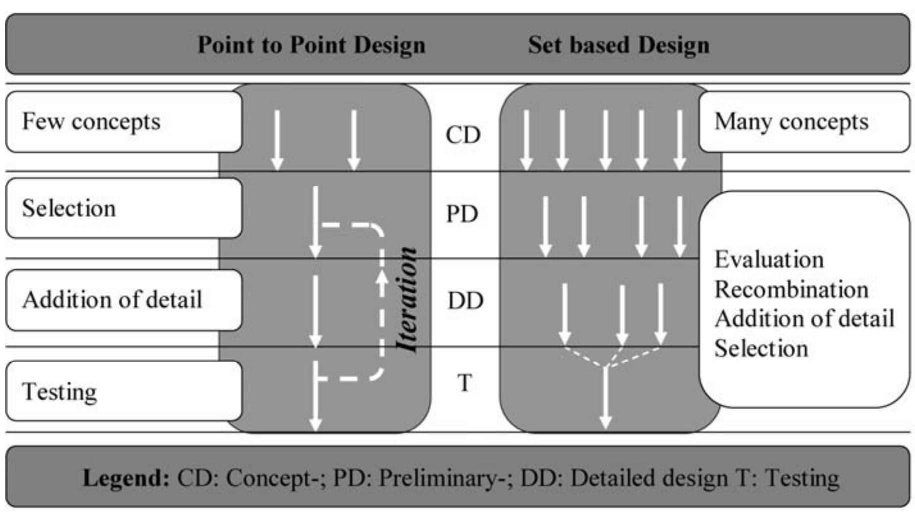

Figure 4.2, Progressive car design process – Set based design

However, it delays the selection of the favorite design concept to the testing of prototypes. By doing so thereby allows to gradually narrowing the solution set towards a more global optimum. A great number of design teams work concurrently on detailed design solutions. The weakest solutions will be eliminated at the end of each design stage and the most favorable sets recombined, modified and detailed. (Parson et all, 1999) Thus costly design iterations can be avoided.

5. DESIGN PROCESS COMPARISION

Considering the design process schemes from the perspective of the building construction industry commonalities as well as differences can be noticed. The focus lays thereby on the number and purpose of the design stages present and the integration of design iterations.

5.1 Commonalities

1) All product design processes start with documenting the design requirements.
2) The three core design stages present: conceptual, preliminary and detailed design are present in all design schemes. A few of the schemes referred too, might use different names or allocate the subtasks of one stage to a number of others.

5.2 Differences

1) Whilst building and ship industries typically only produce unique products the airplane and car industry manufacture a great number of replicates.
2) All but the building and ship industry trial prototypes and feed the information back to the detailed design stage.
3) The set based picks up on the potential disadvantages of point based design processes finding a feasible solution but not necessarily the global optimum, thereby extinguishing the need for design iterations.

6. BUILDING DESIGN OPTIMIZATION

Many references were found stating research activities in the field of multidisciplinary design optimization in car, (Schenk and Hilmann, 2004), ship, (Brown and Thomas, 1998) airplane, (Antoine and Kroo, 2004) manufacturing. However, multidisciplinary design optimization in building design is still in its early stages.

Disciplinary specific optimization activities are known by Michalek et al (2002) in architectural design and by Wright et al (2004) in mechanical engineering.

When considering the safety and performance product requirements one is attempted to order the products referred too as follows, starting with the lowest requirements for buildings, ships, cars and airplanes with the highest. The order might be questionable however it indicates potential parallels with respect to research efforts invested into multidisciplinary design optimization.

6.1 Architecture

Michalek's work focuses on automating the optimization process of the buildings topology and layout with respect to architectural design. Algorithms dedicated to topology and geometry optimization were implemented to support the layout generation in the architectural conceptual design process. This optimization process used includes two stages:

1 Optimization of geometry: modeling units in defining different user types, sizes, dependencies, number and areas of windows added to the units etc. Opportunities like minimizing heating, cooling and lighting costs are optionally available.
2 Optimization of topology: finding the best set of relationships between rooms in a space.

The combination of these two algorithms supports the identification of the mathematical geometric optimum under predefined constraints.

6.2 Mechanical Engineering

Wright dedicated his research efforts to the concept generation and optimization using genetic algorithms applied to mechanical systems and their control mechanisms. His published research was furthermore dedicated to investigating the feasibility of applying more than one assessment criteria simultaneously to the search for the mathematical optimum. Exemplary, the designer has the possibility to assign a weighting factor to assessment criteria such as thermal comfort and system efficiency. The weighted sum will than form a single design criterion which will result in the best discipline dependent most suitable solution for the specific problem area. The implementation of different value drivers or assessment criteria for design concepts is called multi-objective genetic algorithm (MOGA).

7. PRELIMINARY CONCLUSION

Even so the design process used by the construction industry is the eldest in between the four considered it became visible that it is not the most advanced.

The three different design processes identified: point based, set based and design spiral show a great diversity across the industries. Whilst all processes have the three core stages in common: conceptual, preliminary and detailed design they differ significantly in considering design iterations. Whilst the process of re-examination is the traditional character of design it should be recognized as an integral part of the process. However, as design iteration add to the building costs it the common practice to reduce their number to a minimum.

The physical extend of the building product makes prototyping and testing difficult. However, theoretically considered valuable performance evaluation is missing when compared to car and airplane manufacturing. One potential option could be to extend post occupancy evaluation exercises to check if the design requirements have been met.

The set based design shows the great benefit to overcome issues such as design decisions taken to early. However it might not be applicable to the building industry in its full extend as delayed design decision cause the danger of hindering the process.

Design team integration is essential to optimize design concepts during the design process as the optimized concept dedicated to one particular design discipline might cause others to redesign their concepts.

In order to successfully optimize design concepts early during the design process it is essential to integrate the multidisciplinary design teams. Each disciplinary representative is required to have at least a basic understanding of the requirements of the other participating engineering disciplines.

8. FUTURE WORK

The authors will arrange further design team meeting observations to gain a clear insight to project team setups and responsibilities.

Effort has been invested to use discipline specific multi objective design optimization. However little is known about efforts to combine multidisciplinary objective for a holistic concept optimization. The literature review will therefore be continued to identify algorithms to contribute to this area.

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