EVALUATION OF EFFICIENCY IN HOUSING CONSTRUCTION DESIGN

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In housing projects a lot of time is spent for rework, entailing the risk of additional costs, time and deficient quality. As much as 50% or more of rework is originated in faulty output from the design phase. Activities within this phase are strongly interrelated and are carried out by several design consultants. Once the sequence of work in an ongoing project is interrupted the risk for loosing control is high. This results in, e.g., poor coordination of project participants, necessary changes in schedules, possible time pressure and about all a higher risk for making errors. The goal with this study is to reduce the risk of work sequence interruptions in the design phase of housing projects, or in terms of Lean, to make activities in the design phase flow. A timber housing multi dwelling building project in Sweden has been mapped in detail. In total 212 activities have been observed and recorded, spanning from the sales to the erection phase. Iterations (rework) have been identified by using process mining techniques in combination with supplemental interviews. A map of the complete design process consisting of 112 activities (exclusive of iteration) has been derived. A measurement model to detect process regions with a high share of iteration has been proposed that, together with the process map, serves as a starting point for further process optimisation. The efficiency of an activity is assessed by comparing the working hours, ignoring the time used for negative iteration (waste), with the working hours actually used to execute this activity. A Pareto-analysis of the occurring iteration with negative impact on quality then provides an indication of a suitable order for process optimisation.

Keywords: design phase, efficiency, measurement, modelling, standardisation.

INTRODUCTION

This study is about measuring and evaluating efficiency in the design phase of open building projects and about disclosing problematic process regions, i.e., regions in which plan deviations (interruption) emerge.

According to Josephson and Hammarlund (1999) design errors are one of the biggest causes for waste in construction. Analysing defect costs and their causes of 7 building projects, they found that 32% of additional costs were originated in early project phases, i.e. related to client and design, and furthermore that in 3 projects design defects were the largest.

The long term objective of this study is to increase the output's quality of activities in the design phase in order to lessen time needed for rework in construction work in downstream processes.

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Project optimisation tools cited in literature for project management indicate that focus is mainly on effectiveness; e.g. Lean Design (Koskela *et al.*, 1997), Value Network Mapping VNM (Khaswala and Irani, 2001), Analytical Design Planning Techniques ADePT (Austin *et al.*, 1999), et cetera. Effectiveness is about to do the right things (Drucker, 2007:1). Increasing effectiveness successively, i.e., developing and improving working methods, resource consumption and thus project costs will decrease. But in order to lower project costs, efficiency should also be considered (Figure 1). Efficiency is more about how to do things right (Drucker, 2007:2). In this paper, efficiency is a measure about how chosen methods are implemented.

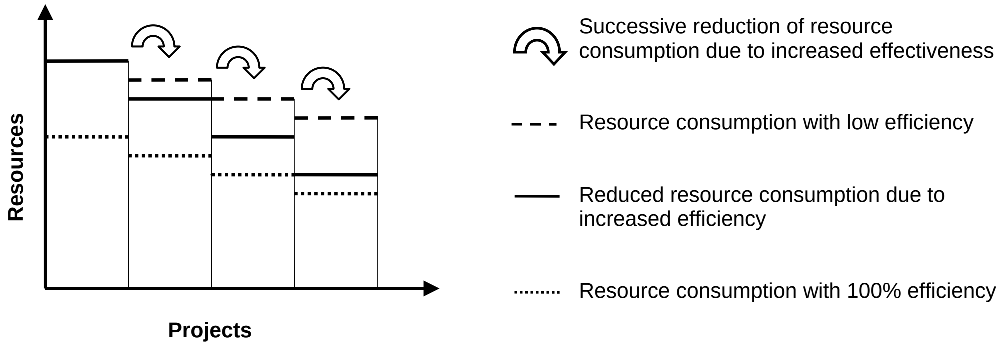

Figure1: Reduced resource consumption due to increased effectiveness and efficiency

Within Lean philosophy, efficiency is mainly considered to enhance the production line of a company, e.g. in value stream mapping VSM (Rother and Shook, 2003) and VSM derivates (Braglia *et al.*, 2006; Khaswala and Irani, 2001). Such optimisation concepts often premise constant processes (Khaswala and Irani, 2001; Yu *et al.*, 2009; Braglia *et al.*, 2006), i.e., standardised activities, high predictability and so forth. In open building projects, these premises are not or just partly fulfilled. Building projects are short lived organisations with varying constellations of project participants (Wikforss, 2006). Furthermore, building projects are often affected by uncontrollable factors, e.g. access to the building site, weather conditions (Yu *et al.*, 2009) or building standards. However, building projects often include sub-processes which can be considered as highly repetitive and are reused in many projects (Söderholm and Johnsson, 2008). In order to systematically perform an efficiency optimisation it is necessary to get an objective, i.e., measurable, picture about the current state of a process (Rother and Shook, 2003). A common way in Sweden to estimate the efficiency of building projects is to compare costs or time per area or volume (Söderholm and Johnsson, 2008). This measure allows comparing the results with similar projects but does not disclose problematic process regions in detail.

The aim of this study is to derive a method to find and standardise repetitive sub-processes and thereby facilitate a stepwise optimisation of building project design for certain building systems. An approach to gauge the condition of the design flow by disclosing inefficient process regions in an objective way is presented. In order to demonstrate this approach a case study was performed investigating the design and construction of a multi dwelling timber housing project (open building project) in Northern Sweden. The data was collected from April, 2009 to January, 2010.

CONCEPT OF OPTIMISATION

Lean Thinking, the Flow Principle and Kaizen

The theoretical background of this study is to be found in Lean-thinking. Lean-thinking is a process-optimising-concept based on the minimum-principle, i.e., a certain aim should be reached with a minimum consumption of resources (Rother and Shook, 2003). In order to identify ways to transform production systems so that waste; i.e., avoidable consumption of resources, can be minimised, ideally five principles should be combined: (1) precisely specify value in terms of a specific product, (2) identify the value stream for each product, (3) make value flow without interruptions, (4) let the customers pull value from the producers, and (5) pursue perfection (Womack and Jones, 2003:16ff).

Value can only be defined by the ultimate customer, respectively the client, and have to be expressed in terms of a specific product in order to meet the client's needs at a specific price and a specific time (ibid). Information transformation fulfilling the client's needs has to be considered during the whole process. Upstream activities should be derived from downstream activities (ibid). In the design phase client's needs are reflected in, e.g. drawings and estimations of cost and time. A prerequisite, following the minimum principle, for realisation of the client's needs in the design phase is the unimpeded transmission of this information between all project participants and from activity to activity, i.e., an unimpeded design flow without interruptions. The design flow is often interrupted by unforeseen events, e.g. faulty output of activities, late changes in client specifications, deviation from the time schedule etc. This can result in a chain of unplanned activities and iteration. Of course, some of this work is creative design, but some is pure waste (Ballard, 2000). To increase process efficiency, the number of non-value-creating iteration in a design process has to be reduced (Pektas and Pultar, 2005).

Assuming an already stable process, Kaizen (changing for the better) can be applied to increase efficiency, where the idea behind is that processes should be enhanced continuously and in small steps (Imai, 1986). The theory of constraints (Goldratt, 1990) implies that interactions between different problems exist, i.e., lowering of one problem could lead to increasing of another one. By optimising, focus should be laid solely on the most problematic process regions. Once these regions are improved other will appear as more problematic. By applying Kaizen and focusing on the most problematic process regions one at a time flow will emerge (Björnfot *et al.*, 2011).

Effectiveness and Efficiency

Effectiveness is about to do the right things (Drucker, 2007:1). In this work, effectiveness is referred as the resulting value of en effort divided by consumption of resources involved.

Let v be the values of the outputs of a process, m the methods available to transform the inputs into output of the process, and rm the amount of resources necessary for the transformation by applying method m. The effectiveness of a process can then be written as:

$$effectiveness = \frac{v}{r_m} \quad (1)$$

Consequently, the effectiveness of a process can be increased by either increasing value v or by decreasing the amount of necessary resources rm.

Efficiency, in contrast, is about to do the things right (Drucker, 2007:2). In this work efficiency is considered as the amount of necessary resources divided by the actually consumption of resources involved.

Let r be the amount of actually consumed resources for producing value v, and 0<rm<r. The last restriction reflects that rm is the minimum amount of resources needed to create value v. The efficiency of a process can then be written as:

$$efficiency = \frac{r_m}{r} \quad (2)$$

Consequently, the efficiency can be increased by either reducing the actually consumed resources r or by increasing rm. Note that the amount of necessary resources rm is related to the chosen method. Increasing rm means to choose a more resource-intensive method, thus to lower the effectiveness.

Consider that costs c are proportional to the amount of consumed resources, i.e., the higher the amount of consumed resources the higher are the costs and vice versa.

Because of the relation between costs and consumed resources we can write equation 2 as:

$$\alpha \cdot c = \frac{r_m}{efficiency} \quad (3)$$

This means that the costs for a defined value are increasing either when the amount of necessary resources is increasing or when the efficiency is decreasing.

Considering v as constant and because of equation 1 we can state then that the costs get minimal when the effectiveness get maximal and the efficiency strives toward 1. In simple words, to minimise process costs, resource-economic methods have to be applied and these methods must be realised as efficient as possible.

The assumption in this paper is that the efficiency of a project is a matter of implementing the chosen methods, where a good implementation stands for a low consumption of resources. Assuming that the effectiveness gets changed between different projects rather than during a project, rm can be held constant during a project. Because of equation 3 the efficiency of a project then can be estimated by costs. Denoting the project costs c as sum of the minimum costs and additional costs, equation 3 can be written then as:

$$efficiency = \frac{r_m}{\alpha \cdot (c_{\min} + c_{additional})} \quad (4)$$

Increasing additional costs implies a lowering of efficiency.

Additional Costs-Causing Activities

According to Josephson and Hammarlund (1999) design errors are one of the biggest causes for waste in construction. Romberg and Haas (2005:58) states that 70% of errors in a process originates in the design. According to Pfeifer (1996:11) and Burghardt (2000:384) the costs of undoing errors is higher the later in a process the error is corrected. Furthermore, Björnfot (2006) and Tribelsky and Sacks (2010) states that working continuously cause less errors than working with interruptions. Thus, a main variable for increasing efficiency in open building projects is a workflow in the design phase free of interruptions.

Causes for interruptions are e.g. insufficient communication (Wikforss, 2006), insufficient arrangement of the work sequence (Pektas and Pultar, 2005), and deviations from the time schedule (Ballard, 2000). Interruptions of the flow results either directly in additional work, e.g. consultant A has to do some additional work because the input for a certain activity he got from consultant B was not accurate, or indirectly via iterations (Ballard, 2000; Pektas and Pultar, 2005). Thus, reducing causes for design-flow-interruption should result in reduced need for iterations and thereby reducing unplanned working time (waste). The problem hereby is that the converse of this conclusion is not valid for every case because an increasing amount of working hours and iterations does not necessarily indicate lower design-flow efficiency. For creative processes, a certain amount of iterations can be assumed necessary in order to assure quality or to simply meet client demands (Ballard, 2000; Yassine and Braha, 2003).

THE PROPOSED APPROACH

A considerably share of additional project costs derives from faulty output of the design phase. Furthermore, these faulty outputs are mainly results of design flow interruption. Figure 2 shows the digraph of the information flow of the case project. The vertices (circles) depict the project activities and are numbered consecutively from top left to bottom right. The numbering corresponds to the sequence of work. The arcs show in which activities the output of a certain activity serves as input. It is obvious that once the workflow is interrupted, it can be difficult to keep full control of the design process. Errors will emerge because of uncertainty, time pressure when attempts are maid to not fall behind schedule et cetera.

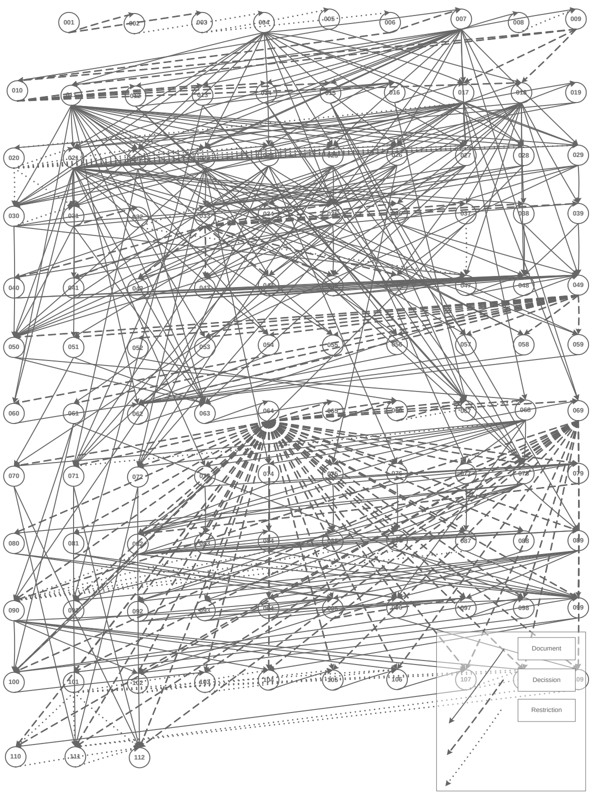

Figure2: Digraph of information flow of the case-project

The design phase of open building projects consists of activities which can be considered as routine work and activities which, in terms of resource consumption, are rather unpredictable (Figure 3), e.g. activities of creative nature or when decisions have to be done. The latter named activities are referred here as non-routine activities. Errors in the planning phase become visible due to iterations in routine activities (negative iteration) respectively due to resulting additional working hours (waste).

Referring Goldratt's theory of constraints (Goldratt, 1990) and Kaizen, control over the design flow will increase by disclosing the routine activities with the biggest share of waste and trying to reduce the causes for waste.

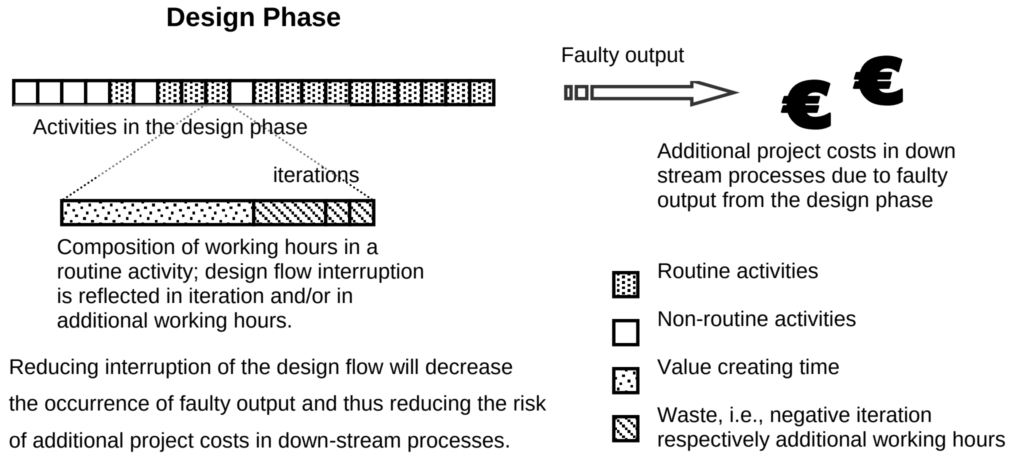

Figure 4: Measuring waste in the design phase

Procedure of the Approach:

4. Compile a standard process for a certain building system as referred in Haller and Stehn (2010).
5. Identify activities within the design phase which can be assumed as routine work. The Cambridge dictionary defines routine as "a usual or fixed way of doing things". Routine activities are the activities which are not or just slightly affected by uncontrollable factors, e.g. interference of the client, abutting owners, local authorities, etc. Furthermore, iterations in routine work are caused only by errors. Creative activities are not routine work. Finally, only activities and sub processes that will be repetitively used in coming projects can be considered as routine work.
6. Measure the working time of every routine activity.
7. Compute the waste time of every routine activity by summing its working hours consumed for negative iteration (Figure 3).
8. Disclose, in terms of process interruption, the most problematic regions in the design process by identifying the routine activities with the highest amount of waste (Figure 3).
9. Scrutinise these activities and find the underlying problems, e.g. with help of further interviews, as a base for further design flow efficiency optimisation.
10. Supervise the development of the design flow by comparing the efficiency of the design phase of the current with preceded projects. The main resource in the design phase is working time. Considering equation 2, the efficiency of the design phase can be estimated by replacing rm with the value creating time tv (Figure 3) and r with the sum of value creating time and waste w:

$$efficiency \approx \frac{\sum_{i \in R} t_{v_i}}{\sum_{i \in R} (t_{v_i} + w_i)}, \qquad (5)$$

where R is the set of routine activities within the design phase. The share of visible waste will not only decrease by reduction of rework but also if the amount of undetected faulty output increases. Thus, the share of additional project costs (Equation 4) has to be supervised as well in order to ensure process enhancement.

THE CASE STUDY EXAMPLE

The empirical data originate in a timber housing project, performed as a design-build project. The building is a two storey apartment building with an area of 1100 sqm, constructed with Masonite's Flexible Building-system (MFB). The project team consisted of SME contractors and consultants. The data collection was an iterative process and the map was compiled stepwise between September, 2009 and September, 2010. The compiling of the map is further described in Haller and Stehn (2010).

Data Collection Methods

The project was mapped in a work step level, i.e., all activities where information in form of documents and agreements or material was transferred between at least two of the main actors were logged. The term main actors refers here to the project participants who were responsible for the execution of each a part of the project phases and thus participated in the project meetings, these are the architect, the main contractor, the wall element manufacturer, the building system supplier, the project manager, and consultants for the technical design, acoustics, plumbing, electricity, and underground engineering. The log file of the project activities provided descriptions of the respective activities, the date of execution, working hours and the required inputs. In order to triangulate the data the contents of the log file were discussed with the project leader during 10 meetings. Possibly ambiguity was clarified and the log entries adjusted if necessary. To further ensure the correctness of the logged activities, knowledge of proceeding details was collected during 14 project-meetings, where 5 of them were telephone-meetings. From the adjusted log file a project map was derived using so called EPC diagrams as described by van der Aalst (1999). The EPC diagrams were created iteratively and presented during three meetings to the main actors and successively adjusted. Once the correctness of the adjusted EPC diagrams was accepted by the main actors the whole process was entered into a Design Structure Matrix DSM (Steward, 1981). To validate the DSM process map, concerning the linkage of the work steps, the main actors made a final check.

Finally the activities with the highest share of waste (Figure 3) were detected by applying an ABC-analysis (Pareto) (Step 5 in the procedure).

RESULTS

A map with 112 activities was compiled where 101 activities are allotted to the design phase (Figure 4, Table 1).

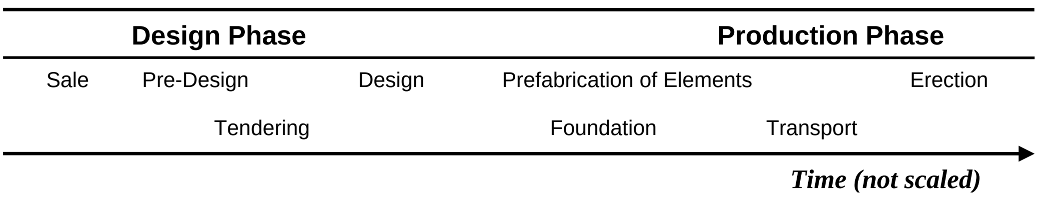

Figure3: Scheduled organisation of the investigated project

The analysis of the project costs, executed by the main contractor at the end of the project, shows that the additional costs in the erection phase (Figure 4) amounted to 9% of the total project costs. Furthermore, the main actors estimated that about 50% of these costs can be related to planning errors. No numbers were available about the shares of additional costs of the design phase and prefabrication of elements. But assuming that the costs of the design phase mainly derive from working hours, the share of additional costs can be estimated to be about 1% of the total costs. The building panels were produced industrially, thus the share of additional costs there should be relatively small.

Table 3: Activities in Sub-Processes

Sub-Process	No. of Activities	No. of Routine Activities	Waste [h]
Sale	3	1	0
Pre Design	30	7	11
Tendering	31	25	16
Design	37	28	255
Production Phase	11	x	x

73% of the activities within the design phase could be classified as routine activities (Figure 3, Figure 5a, step 2 in the procedure), which corresponded to 41% of the working hours of the design phase. The results of the ABC-analysis (Pareto) show that 80% of waste in the design phase originates in only 15% of the routine activities (Figure 5b, step 5 in the procedure). All of these activities were included in the design process (Table 1). The efficiency of the design phase (Equation 5) is estimated to be 80%.

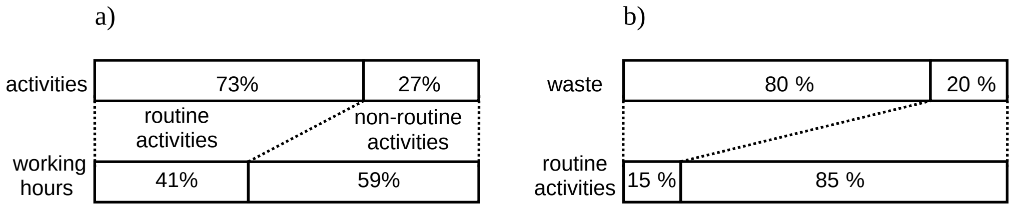

Figure 4: Relationship between activities and waste in the design phase.

DISCUSSION

The main share of additional costs (9%) was in the erection phase. It has to be considered that this number was compiled by the main contractor who was responsible for both design and production and thus had an interest in reducing consultant costs. The importance of an accurate output of the design phase is strengthened by the estimation of the project participants that 50% of the additional costs in the erection phase results of undiscovered planning errors. A Comparison of 4,5% (50% of the additional cost in the erection phase) of the project costs with 1% additional project costs from the design phase further backs the assumption that by optimising process efficiency of the design phase (in terms of resource consumption) focus must be laid on improving the design flow instead of reducing working hours. The results given in table 1 indicate that the main share of routine activities is in the tendering and design process. Comparing 16 hours waste of the tendering process with 255 of the design process shows that the latter process was the most problematic one in terms of rework, which corresponds to the findings of Josephson and Hammarlund (1999). The results show that 41% of the working hours of the design phase originate in routine activities. However, taking into account the theory of constraints (Goldratt, 1990), the results of the ABC-analysis (Pareto) indicate that enhancing the design flow in this case should be started by focusing on about 15% of these activities.

The efficiency of the design phase is about 80%. That means that if waste can be reduced the efficiency should be higher for the next project. But the measured efficiency will also increase when fewer errors in the design phase are detected. Fewer detected errors lead to fewer rework in the design phase but, according to Pfeifer

(1996) and Burghardt (2000), to higher costs in downstream processes. Thus, the efficiency of the design flow actually can only be considered to be increasing when the measured efficiency is increasing plus the share of additional costs for the project is not increasing (Equation 4).

CONCLUSIONS AND FUTURE WORK

In this paper an approach to estimate the condition of the design flow in open building projects is compiled to increase project efficiency. A considerable share of additional working hours arises from errors in the planning phase which in turn are closely connected to interruptions of the design flow. The idea of the presented approach is to disclose problematic process regions by measuring the amount of additional working hours of activities within the design phase that fulfil certain qualifications, i.e. they must be repetitive between or within projects, controllable and must not be of a creative nature. The efficiency then can be increased by focusing on the most problematic process regions.

As a basic problem concerning the quality of the design in open building projects lack of time was mentioned. Most of the participating companies were forced to excess their capacities due to competition pressure by dealing with to many building projects at once. It should be investigated how DSM could be used to gain advises about on which activities the most effort should be laid to a certain point of time.

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