DESIGN PROCESS MODELLING TO MEASURE ENGINEERING PRODUCTIVITY IN BUILDING DESIGN

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ABSTRACT

A multi-domain Matrix (MDM) is used to identify and analyse rework loops within the Building Design (BD) process caused by building regulations. To model this process, we used information from official documents, plans of work, email archives, and anecdotal evidence as a case study. Findings reveal that MDM can identify the rework loops caused by building regulations, this information forms the basis to improve current BD processes. The complexity of the rework loop including the processes, people and, deliverables involved in the rework loop is also identified. Further analysis can also use the MDM to estimate the costs incurred with each rework cycle. This MDM can also identify rework loops in other engineering design processes due to design changes.

This study is part of a PhD project exploring engineering productivity in the construction industry using DRM. The results present an MDM that provides situation-specific insight, offering areas of process improvement, and support through engineering productivity measurement. This is one of the few studies that models rework loops in the BD process caused by regulations.

Keywords: Process modelling, Design process, Design management, Building Design, Engineering Productivity

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1 INTRODUCTION

The construction industry has suffered for decades from significantly poor productivity relative to other industries. This longstanding problem has not been addressed effectively as over the past ten years less than one-quarter of construction firms have matched the productivity growth achieved in the overall economies in which they work (Barbosa et al., 2017). One of the main contributing factors to poor productivity in the construction industry is rework, where rework is defined as "the unnecessary effort of redoing a process or activity that was incorrectly implemented the first time" (Love, 2002; Dixit et al., 2019).

In the myriad of studies identifying the sources, factors, issues, and impacts of rework in construction projects, Love's (1999) causal model showed that rework in construction projects is caused by errors made during the Building Design (BD) process. Design process modelling is one of the many methods employed in research to document and analyse various aspects of design processes, and hence we assumed that such modelling would be suitable to identify and analyse rework in BD.

Current research in construction management provides various process models to address rework but focuses on the manufacturing and construction stage (Fig. 1), few models address rework and its causes in BD- Improved Critical Chain Design Structure Matrix (Ma et al., 2019), Design Construction Reduction Model (Love et al., 2000), Artificial Neural Model (Palaneeswaran et al., 2006), and Rework Generic System Model (Forcada et al., 2017). These models, however, were found not fully suitable (see Wong 2021b) for our aim: to understand rework in BD due to regulatory checks and how it can be identified and quantified, as part of a PhD project exploring how engineering design productivity in BD is impacted by rework. One domain with a long tradition of process modelling and iterations (or rework in BD) is engineering design research.

1.1 Process modelling in engineering design

To select process models from engineering design research for our modelling objectives, it is important to understand the differences in the design processes as far as relevant to rework modelling to ensure the selection of an engineering design process model that can be used for BD process modelling. Table 1 lists the differences between BD and engineering design processes as far as relevant for rework.

Table 1. Comparison of rework-relevant process characteristics of building design and engineering design

Building Design (in our context)	**Engineering Design**
Unique, one-off design Failure in design is not immediate, design failure rectification post-production is challenging and costly if not impossible	Usually not one-off, and often largely based on previous designs. Customer/ user feedback from failed design is immediate, and changes in production and design is possible postproduction
Design errors/discrepancies are audited and regulated	Designers to design and test to comply to regulations/ design standards
Rework due to changes mandated by regulators	Iteration to improve design, solve design issues
Mandatory to change, autonomy in regulators	Autonomy to change in designers/ within company

Many process models are used in engineering design research. Wynn and Clarkson (2018) categorised these into procedural models, analytical models, abstract models, and management science/operations research models. We have chosen analytical models to meet the modelling objectives for our BD process as they "provide situation-specific insight, improvement, and/or support which is based on representing the details of a particular design and development process instance" (Wynn and Clarkson, 2018). From the analysis of several analytical models, we selected the Design Structures Matrix (DSM) and its variants as the most suitable engineering design process models to document and analyse rework in BD processes (Wong et al., 2021b).

This paper shows how DSM can be used in BD to identify and quantify rework loops. In Section 2, we introduce rework in BD using our case study. In Section 3, we discuss rework in DSM models and the choice of domains used in the Multi- Domain Matrix (MDM), a variation of DSM, to model the BD process. In Section 4, we discuss the method employed and the data collection for the MDM. The resulting MDM model and the insights obtained from the analysis of the MDM model are presented in

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Section 5. Section 6 discusses the results and some of the limitations. The paper concludes with a short reflection in Section 7.

2 REWORK IN BUILDING DESIGN

In our research, we define the BD process as the process from the Concept Design stage to the Technical Design stage of producing Structural Plans (which includes design calculations and drawings of the details of all building elements), which corresponds to stages 2 to 4 of the RIBA (2013) Plan of Work (See Fig. 1). Only when Structural Plans are approved by the regulatory authorities, can manufacturing and construction commence.
Using Singapore's construction industry as a case study, we established that substantial rework occurs in the design stages due to design changes arising from errors detected through checks of Structural Plans as part of the pre-submission and submission processes required by these authorities (Wong et al., 2021b). Our literature review revealed only few analyses to fundamentally understand how error detection and regulatory checks affect rework in construction projects. This understanding is the foundation for identifying and quantifying rework and improve the BD process.

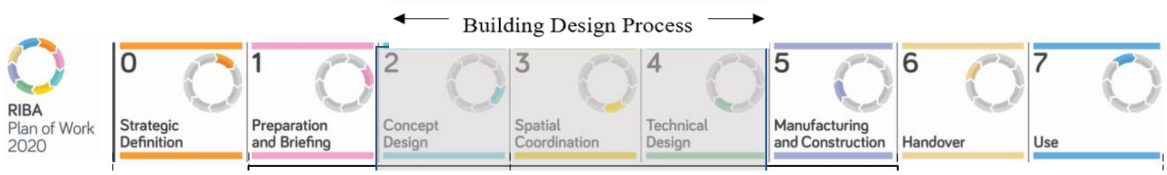

Figure 1. Stages of construction projects defined in the RIBA plan of work

The building regulation we are studying is the Structural Plans and Permits Approval Process (SPPAP), are summarised in Figure 2, showing the submission preparation process (blue arrows) and the approval process (black arrows). See Wong et al., (2021b) for details and other processes. To prepare submission of the structural plan to the regulatory authority for approval, the architect, engaged by a client (owner of the land) submits the completed set of drawings of the building to a so-called Qualified Person (QP), a structural engineer and a so-called Accredited Checker (AC), both engaged by the client. It is important to note that Architect and QP may or may not be from the same company, the AC must be from a company different from that of the Architect and QP. The AC and QP independently produce a set of structural plans, showing all structural details, from the Architect's drawings, which only show the skeleton of the building elements. The structural plans of the AC are used to check against those of the QP. Based on the experience of the first author, the AC's structural plans are often a less refined but still viable estimates of the structural integrity of the building, i.e. the building design would pass the applicable building code. The AC is selected through a bidding process, bringing down the cost and hence the available resources. The QP corresponds with the AC about the structural plans. He/she only corresponds with the architect if the skeleton requires changing. Once QP and AC agree, and no more changes to the skeleton are required, they both endorse each document in the submission package, which is then submitted by the QP to the regulator authority for approval. This authority checks all documents, but focuses on the Structural Plans to identify any errors in the plans and calculations, any missing details, reporting discrepancies, etc. Any issues are referred to the QP through a written direction, copying the Architect and AC in the correspondence, and the submission preparation process is executed again. This may or may not involve changes to the skeleton provided by the Architect. Any project will have many (up to hundreds) submission packages, one each for a group of structural elements. The project manager determines the content of a package based on the construction sequence, e.g., in a multi-story building, there may be a submission package for level 1 columns, and another for level 1 beams, etc. As construction is progressing, packages for level 2 and then for level 3, etc. will be prepared. Note that each package (containing architect drawings, structural plans, calculations, and supporting documents) will amount to several hundreds of pages.
The SPPAP process in Singapore may be an example of very strict enforcement of regulatory checks in BD, but the importance of regulatory enforcement to ensure building safety is reflected in disasters such as the collapse of scores of buildings in the recent earthquake in Türkiye (Beaumont, 2023) and in the United Kingdom's new Building Safety Act passed in April 2022 which considers the benefits of mandatory error detection in BD. Regulatory compliance and checks are also prevalent in other processes like business operations (Mustapha et al., 2020) , occupational health and safety (Tompa et al., 2016), and software design (Mubarkoot et al., 2022). In their review, Tompa et al.(2016) further makes a distinction between

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the regulatory approach and the policy levers/ enforcement strategies to explain the regulatory compliance process. In our case study, the regulatory compliance approach is regulatory design checks while the enforcement strategy is an independent design check by an AC followed by the regulatory authority.

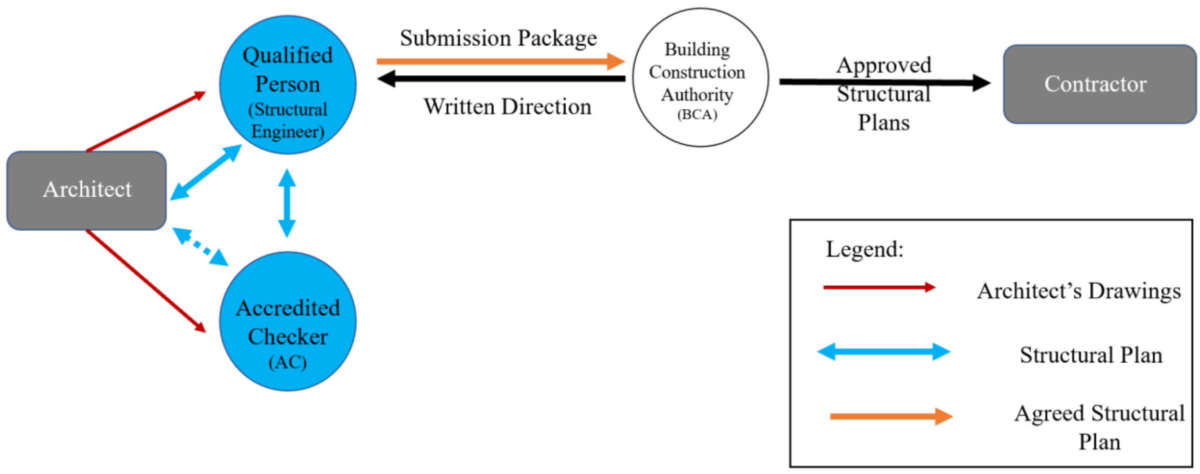

Figure 2. SPPAP in Singapore (adapted from (Wong et al., 2021b)

3 DSM AND REWORK

This section describes the selection of the most suitable DSM model for our objective to identify and analyse rework loops within the BD process caused by the building regulations as described in the previous section.

DSM is a network modelling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture. The advantage of this matrix based modelling is its approach to decompose, identify, analyse, display, and improve the management of engineering system(Eppinger and Browning, 2012). Table 2 below summarises DSM models categorised in Eppinger and Browning's (2012) work that are relevant to our rework analysis.

Table 2. DSM model types and rework analysis from Eppinger and Browning (2012)

Modelling System Architectures	Elements	DSM Analysis
Product Architecture DSM Models	Components and interactions within a physical artifact, such as hardware (and sometimes software)	Identifying interactions, interaction strengths, clustering analysis, sensitivity analysis, interface management, product portfolio management
Organisation Architecture DSM Models	people or teams and their interactions within an organization	Assessing communication needs between teams, rational organisation design, facility layout, application of integrative mechanisms
Process Architecture DSM Models	the actions and interactions that accomplish work, such as the design or production of a product, the delivery of a service, or the execution of software code	Sequencing, Monte-Carlo simulation- activity cost and duration, rework probability, rework impact, finish-start overlapping, learning curves, resource constraints, Eigenstructure-special case of parallel iteration, where coupled activities are executed simultaneously and then exchange information, creating rework as modelled by the DSM interaction values
Multidomain Architecture MDM Models	Combination of two or more of the above system architectures	Identify needs for cross-functional, cross-team interactions, infer intra-domain relationships

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3.1 Choice of modelling domains

In this study, we propose to use an MDM to identify and analyse rework loops within the BD process caused by building regulations, in order to understand the problem of rework in BD. The following sections describes the choice of domains used in the MDM and how we used MDM to model the SPPAP.

For a comprehensive analysis of a process, it is important to select, relate, and integrate all domains that are relevant to the specific analysis (König et al., 2008). Based on Love's (1999) systematic view of rework, elements that could influence rework in a construction project include: Training skill level, employee motivation, incentives and rewards, participative decision-making, partnering/ strategic alliances, process improvement programme, customer needs/ client brief, human support, motivation, resource planning, innovation, procurement, operating environment, technical support, and technology level. These elements are categorised into four domains and modelled in our MDM: People, Deliverables, Products, and Processes. The significance of these four domains to our modelling objectives is discussed below.

3.1.1 People

As the analysis of the MDM model includes deriving an Engineering Productivity metric for the structural engineer's design process, we are interested in people that are directly involved in the design process of the structural engineer. In other words, we are taking the perspective of a structural engineer when modelling the BD process. Examples of individuals omitted in the model are project members in the Architect team, Accredited Checker team, and Building Construction Authority team (Refer to Figure 2). The Architect team, Accredited Checker team and Building Construction Authority team will be simplified to a single point of contact with the structural engineer. This simplification would omit the internal design and approval process within the respective teams.

3.1.2 Process

The process model focuses on the structural engineer's workflow. This broadly includes design calculations, documentation, drawings preparation, internal design review/ approval, submission report and form preparation. In the MDM model, these processes will be modelled in greater resolution including subtasks to adequately capture the rework loops in an engineer's workflow.

3.1.3 Deliverables

As the MDM aims to identify rework loops in the authority submission process, the deliverables are the submission documents and the corresponding documentation and items required to produce them.

3.1.4 Product

The final product of a BD would be the approved Building Plans (design calculations and drawings). The products we are modelling in MDM will be the approved building plans grouped into structural components of a building, for example, beams, columns, slabs, foundations etc. This grouping of Building Plans is common industry practice and also coherent with authority submission packages in Singapore.

Data for other variables affecting these four aforementioned domains are also collected for the MDM model as they influence Engineering Productivity and will be used in further analysis, they include nominal duration of processes, labour costs, technology adoption level, etc.

4 METHODOLOGY

4.1 Case study

A 60,000 sqm, a 4-storey reinforced concrete building project in Singapore was used as a case study to test the effectiveness of MDM to identify and analyse rework loops in BD caused by building regulations.

Due to Covid-19 restrictions, it was not possible to carry out participant observation in engineering design firms to collect data. Instead, data was primarily collected from anecdotal evidence and a forensic study of email archives for the chosen construction project. Anonymised information from email archives was retrieved which includes time stamps of emails. From the time stamps, it is assumed the period a task is addressed is the time between the email received (task start) and the email replied (task end). We further assumed the everyone involved in the SPPAP allocates 100% of their working hours given the usual urgency of the project.

Other data were obtained from official documents and guidelines on submission processes, and anecdotal evidence from the first author's experience and understanding of the BD process as a practising structural engineer in Singapore.

5 RESULTS

The result of using MDM is presented in Figure 3. Three rework loops are identified, shown as shaded regions in the Process matrix in the MDM. The corresponding People, Deliverables, and Products involved in the rework loops can be easily identified using the MDM model.

Further analysis and calculations for the costs of each rework loop are summarised in Table 3. For detailed calculations and assumptions, refer to the Appendix.

Table 3. Summary of estimated labour costs per rework cycle

Rework Loop	Estimated labour costs per cycle (k$/week)
1	12
2	9
3	27

6 DISCUSSION AND LIMITATIONS

The contribution of this study is the application of MDM to document and analyse complex engineering processes with mandatory regulatory checks occurring post technical design and preceding manufacturing. The MDM can not only identify rework loops and bottlenecks in the BD process, but the further analysis also estimates the costs of each rework cycle. The results can inform other engineering design processes of the costs of mandatory design checks and be included in process planning and decision making.

Building designers can benefit from future work by the authors that will present an evaluation of the integrated MDM-based engineering productivity metric. The metric aims to be incorporated into building design projects as a self-assessment tool thereby streamlining the design process. With an improvement in the building design process, the productivity of the AEC industry would consequently improve.

The limitation of the study is the data collection method. A more robust, accurate data collection method for the MDM would be thorough participant observation or timekeeping by the participants. Furthermore, the assumptions in the calculations for labour costs in each rework cycle are too general and only present a rough estimate, although they are suitable for a comparison as they are based on the same assumptions. Future work can apply a more detailed numerical analysis method to quantify the costs of each rework cycle using the information in the MDM.

7 CONCLUSION

In conclusion, previous work has established that design process modelling is well-founded in the field of mechanical engineering, and product design and development but not in BD (Wong et al., 2021a). This paper presents the results of using the Multi-Domain Matrix) to identify and analyse rework loops in BD caused by building regulations. This process model should also be applicable to other engineering design processes where substantial rework occurs. With the MDM model, industry practitioners and researchers can better understand rework in the design stages of construction projects to improve rework management in BD.

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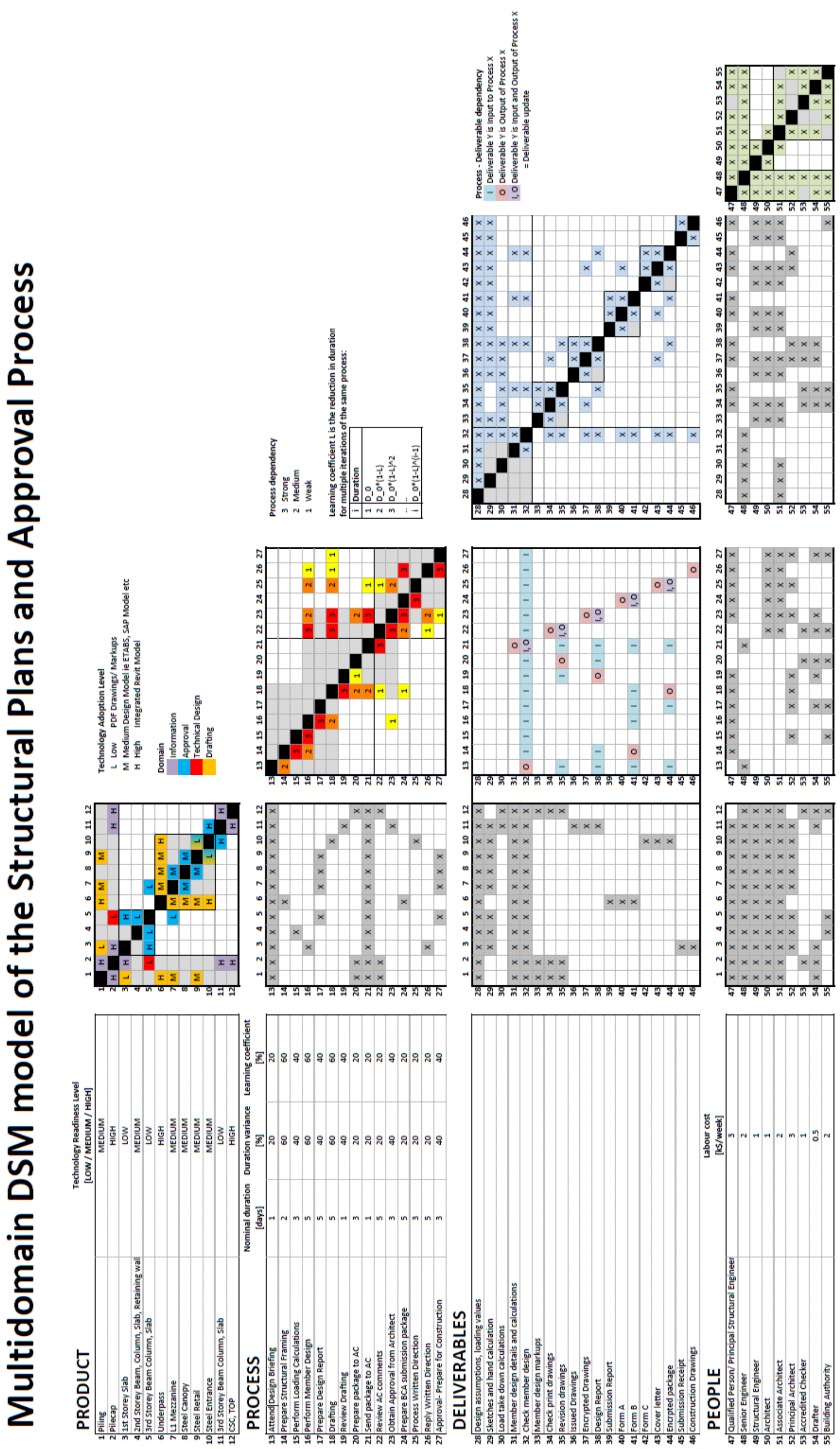

Figure 3. MDM model of the structural plans and approval process

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APPENDIX

Cost calculation for rework loops:

1. Obtain learning coefficients and nominal durations for i=0, from MDM, D_0=> duration for base design
2. Calculate durations for each process for first iteration i=1, D_1 sum process durations => total duration for iteration 1
3. Obtain people involved in the corresponding process steps, P_i
4. Calculate unit labour cost for people involved in the corresponding process steps , L_i=labour cost x P_i
5. Calculate total labour cost for people involved=C_i= L_i x D_i

Assumptions:
A1.The learning coefficient is assumed to be a function of the number of iteration performed.
A2. The total duration of the iteration assumes that all the dependent process steps are activated once.
A3. It is assumed that for every role associated to each task, it will incur the cost of 1 person. For example, for Process 18 drafting, we assume only 1 drafter will complete the task in the duration.
A4. It is assumed that people involved in the process are allocating 100% of their time and labour cost to the task.

Rework Loop 1:

D_0	Process steps	13	14	15	16	17	18	
	Learning cofficient	0.2	0.6	0.4	0.6	0.4	0.6	
	Initial design duration [days]	1	2	3	5	5	5	
D_1	Iteration 1	0.8	0.8	1.8	2	3	2	
D_2	Iteration 2	0.64	0.32	1.08	0.8	1.8	0.8	
D_3	Iteration 3	0.512	0.128	0.648	0.32	1.08	0.32	
	Sum [days]	1.952	1.248	3.528	3.12	5.88	3.12	
L	Per engineer [week]							
	QP		3000	3000	3000	3000	3000	
	SE	2000						
	PA			3000		3000	3000	
	Drafter					500		
	BCA			2000		2000		Total cost (i=1,3)
C_i	Total cost (i=1)	320	480	2880	1200	5100	2400	12,380
	Total cost (i=3)	780.8	748.8	5644.8	1872	9996	4056	23,098

Rework Loop 2:

D_0	Process steps	16	17	18	19	20	21	
	Learning cofficient	0.6	0.4	0.6	0.4	0.2	0.2	
	Initial design duration [days]	5	5	5	1	3	1	
D_1	Iteration 1	2	3	2	0.6	2.4	0.8	
D_2	Iteration 2	0.8	1.8	0.8	0.36	1.92	0.64	
D_3	Iteration 3	0.32	1.08	0.32	0.216	1.536	0.512	
	Sum [days]	3.12	5.88	3.12	1.176	5.856	1.952	
L	Per engineer [week]							
	QE	3000	3000	3000	3000			
	SE						2000	
	PA		3000	3000	3000			
	AC					1000		
	Drafter		500		500	500		
	BCA		2000			2000		Total cost (i=1,3)
C_i	Total cost (i=1)	1200	3900	2400	780	720	320	9,320
	Total cost (i=3)	1872	7644	3744	1528.8	1756.8	780.8	17,326

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Rework Loop 3:

D_0	Process	22	23	24	25	26	27	
	Learning cofficient	0.2	0.4	0.2	0.2	0.2	0.4	
	Initial design duration [days]	5	3	5	3	5	3	
D_1	Iteration 1	4	1.8	4	2.4	4	1.8	
D_2	Iteration 2	3.2	1.08	3.2	1.92	3.2	1.08	
D_3	Iteration 3	2.56	0.648	2.56	1.536	2.56	0.648	
	Sum [days]	9.76	3.528	9.76	5.856	9.76	3.528	
L	Per engineer [week]							
	QE		3000	3000	3000	3000	3000	
	A	1000	1000	1000	1000	1000	1000	
	AA	2000	2000	2000	2000	2000	2000	
	PA		3000		3000		3000	
	AC	1000						
	Drafter	500	500				500	
	BCA	2000			2000		2000	Total cost (i=1,3)
C_i	Total cost (i=1)	5200	3420	4800	5280	4800	4140	27,640
	Total cost (i=3)	12688	6703.2	11712	12883.2	11712	8114.4	63,813

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