Designer Productivity Management in Building Design Using Multi-Domain Matrix Analyses

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Abstract: Rework in Building Design (BD) processes has a multitude of impacts on the performance of construction projects. A Multi-Domain Matrix (MDM) is a modelling technique to identify and analyse the effects of rework and iteration loops on the process and product of complex engineering systems. However, there are fewer MDM analyses on the effect of rework on the productivity of designers. Therefore, we propose an adaptation of an existing MDM to assess the productivity of the BD rework process. We incorporate significant BD productivity factors consolidated from previous work: change impact, design competency, layers of approvals, communication, and technology availability. For the productivity analysis, we present two MDMs of different types of components in a building project. Practitioners can use the productivity MDM to streamline their BD process and improve construction project performance. The designer productivity model can also be adapted to other engineering design processes subject to rework.

Keywords: Multi-Domain Matrix, productivity, redesign, rework, construction industry, building design

1 Introduction

Design changes and redesign due to late identification of design errors in construction contributes significantly to rework in the Building Design (BD) process. (2022; Wong et al., 2023) describe in detail the BD process in Singapore, where mandatory design checks in the technical design stages cause substantial rework and significantly affect project performance.

Design changes and iteration are also common in other engineering design processes. Ahmad et al., (2012) reviewed change propagation concepts and the information domains covered in the concepts. The review shows that people/agents and documents are less covered than other domains. Similar work by Ahmad et al., (2011) also reviewed the literature on information models used to manage engineering change that focuses on requirements, functions, components, and processes. From Ahmad's reviews, we find few analyses on the effect of design changes and redesign on the designers. To address this, this study proposes a new approach to analyse the designer productivity by adapting an MDM for BD, answering the following questions:

1. How can designer productivity factors be incorporated into an MDM for rework analysis,
2. How can the MDM be used to assess the impact of rework on designer productivity?

The following section introduces the problem of rework and designer productivity in BD. The section also describes the existing MDM in BD and proposes a new Productivity MDM. Section 3 reviews previous studies of rework models in construction management research. Section 4 describes the modelling approach to incorporate designer productivity factors into the Productivity MDM. The case study in Section 5 assesses the impact of rework on designer productivity using the Productivity MDM. The paper concludes with a discussion and future work.

2 Rework and designer productivity in BD

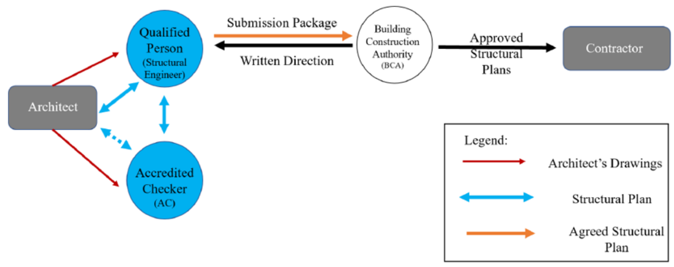
For the scope of this research, the authors refer to designer productivity as the efficiency and effectiveness of how designers perform structural design in BD. Efficiency refers to performing activities with minimum wastage of time and optimum usage of resources so that the work done is faster and error-free (Gager, 2020). This is strongly linked to the utilisation of resources and mainly influences the input of the productivity ratio (Tangen, 2002). Effectiveness is the extent to which someone or something is successful towards meeting the desired outcome (Gager, 2020). This is linked to value creation and affects the output of the productivity ratio (Tangen, 2002). Structural design is the design work to specify structural elements and details of building components within the BD process as performed by structural engineers (designers).

It is essential to understand designer productivity as designers are the main contributors to the BD process, and based on the anecdotal evidence from the first author's experience in BD, a designer's productivity affects and is also affected by rework. Furthermore, most rework studies in construction management and engineering design focus on the effects of rework on the design process and product (i.e., risks, costs, probability, trade-offs etc) and fewer on the designers.

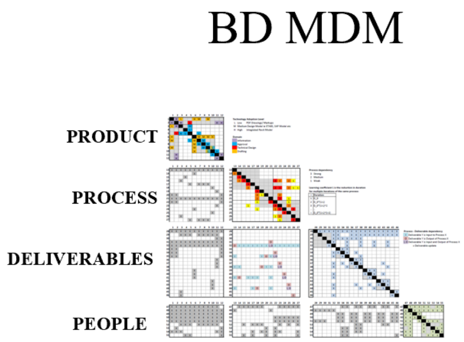
Rework in construction projects refers to the unnecessary effort of redoing a process or activity (Palaneeswaran, 2006). This could include performing changes after the first viable design to reproduce designs, calculations, drawings, submission forms, reports etc. In Singapore, an authority submission process in BD imposes a mandatory design checking system where an accredited checker checks the structural engineer's design. The architect, accredited checker and structural engineer must agree on a final design before submission to the authority for approval (See Figure 1a). This authority submission process results in substantial rework in the BD process. The first author previously used an MDM to represent the authority submission process (Figure 1b). This **BD MDM** identifies rework loops and quantifies the costs of rework in BD due to regulatory checks and authority submission (Wong et al., 2023).

However, the BD MDM does not provide information about how designers' productivity is affected by rework (the causes or extent). This is because the matrices in the People's domain of the BD MDM are binary, merely indicating the presence or absence of a direct relationship with other domains (product, process or deliverables).

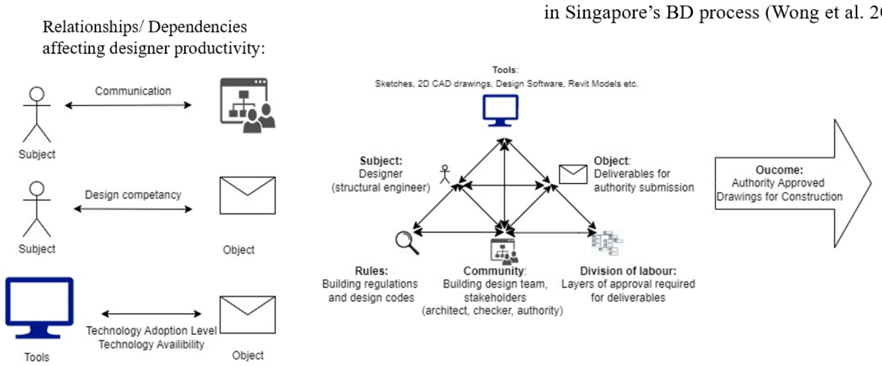
Therefore, we propose including designer productivity information in the BD MDM and adapting it into a **Productivity MDM** (Section 4.1). The Productivity MDM models the relationships and dependencies between domains in the authority submission process that affects designer productivity (Figure 1c). It should be noted that each Productivity MDM documents a single authority submission process, and the same authority submission process is repeated for each group of building components in a building project.



(a) Authority submission process in Singapore's BD process (Wong et al. 2021)



(b) BD MDM to represent authority submission process in Singapore's BD process (Wong et al. 2023)



(c) Abstraction using Activity Theory to represent the BD authority submission process with designer productivity

Figure 1. Simplified BD authority submission processes for MDM analyses

3 Literature review

Current research in construction management provides various analytical process models to address rework but focuses on the manufacturing and construction stages. However, few models address rework and its causes in BD. This section reviews previous work relevant to our objective of using MDM to model rework due to regulatory design checks in BD.

The Improved Critical Chain Design Structure Matrix (ICCDSM) proposed by Ma et al., (2019) is a Design Structures Matrix (DSM)-based model that provides insights for researchers and practitioners through its new framework for rework management. The model combines the advantages of DSM modelling with Critical Chain Project Management and heavily depends on optimisation functions and algorithms to derive an optimal project schedule with minimum rework. This method focuses only on processes in construction projects and does not consider the designers involved.

Palaneeswaran et al., (2006)Artificial Neural model predicts project performance using datasets of cost attributes from BD and construction-related sources. The model predicts cost overruns for building and civil works. The model triangulates knowledge networking with experts and practitioners in the construction industry through interviews, targeted questionnaire surveys and forensic case studies of completed construction projects. However, the high modelling effort makes industry application difficult. The Rework Generic System Model (Forcada et al., 2014; Forcada et al., 2017) identifies factors influencing rework through case studies of completed construction projects. The dynamics of rework are first mapped into a generic influence diagram. Data were then collected to calculate the contract values and duration, which were used to determine the cost of rework in each project. This statistical model helps study the effects of the various factors contributing to rework by applying various probability distribution tests and regression analyses. However, this model does not offer a way to identify and visualise the rework loops within processes. Moreover, this model is applied primarily to data from the manufacturing and construction stages instead of the BD process.

In summary, most of the rework models in construction management investigate rework in the manufacturing and fabrication stages, not the BD stages. For models that analyse the designers in the BD stage, they do not assess the designer's productivity.

4 Modelling approach

The proposed modelling approach is presented in Figure 2. Data is first collected to document the authority submission process. The MDM is then used for both rework and productivity analysis. With the results, the user can perform process improvement and repeat the analysis to streamline the process.

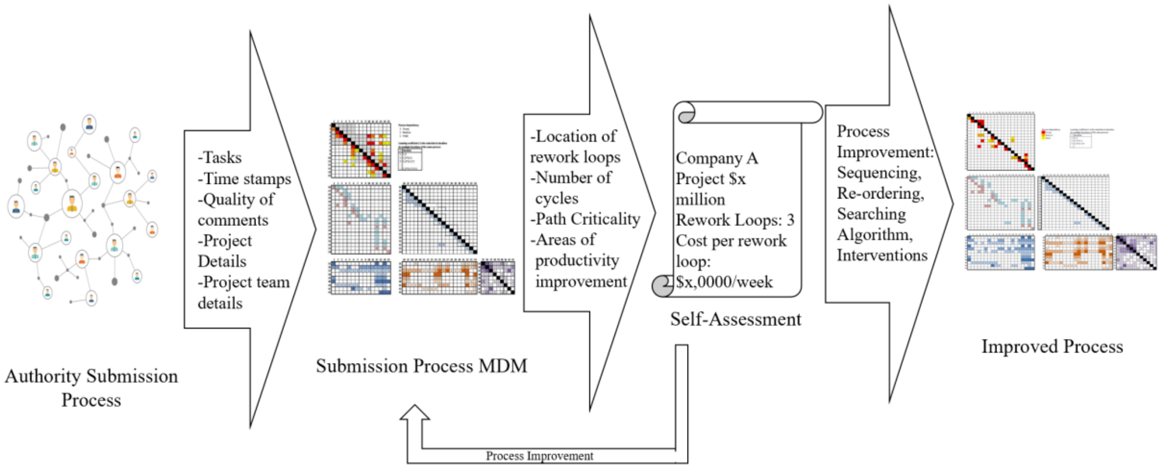
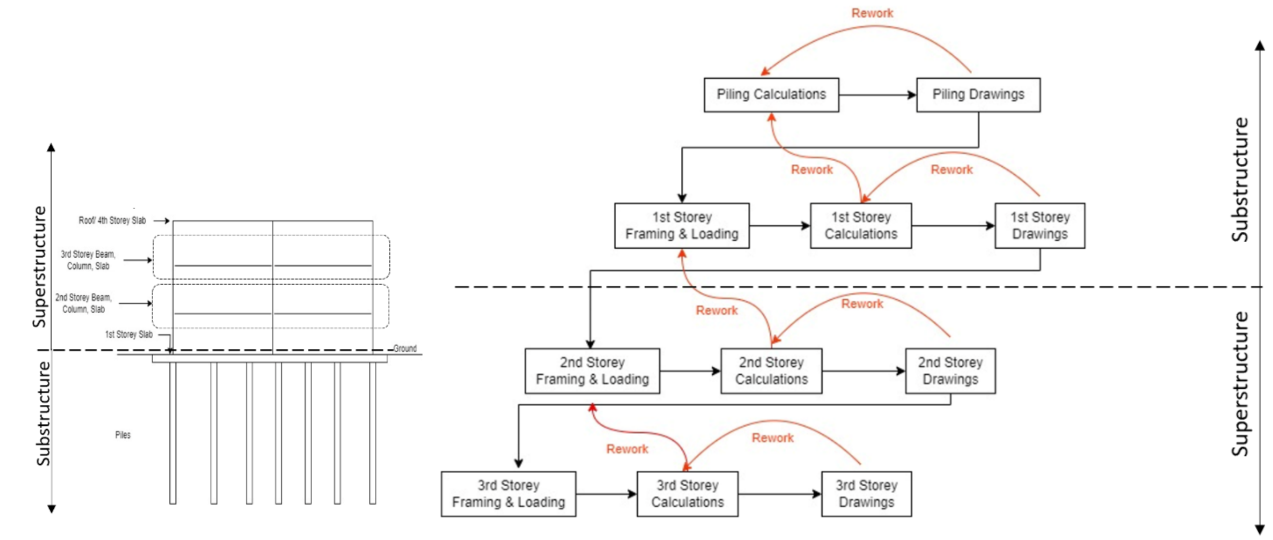


Figure 2. Proposed modelling approach using Productivity MDM to improve the BD process

4.1 Modelling method

The **BD MDM** is adapted into a **Productivity MDM** to include additional data to analyse the designer's productivity. We previously used the BD MDM to represent a high-level authority submission process for a 4-storey building project (Wong et al., 2023). The Process DSM in this BD MDM showed rework loops between the different building components. We further observed that the authority submission processes for each building component are similar, but two groups of submissions are distinct: superstructure and substructure submissions.

- Superstructure Submission: these documents are for building components that are overground and only require qualified structural engineers for design, checking, and submission,
- Substructure Submission: these documents are for building components that include any ground/underground design and require qualified structural and geotechnical engineers for design, checking, and submissions.



(a) Building components in a typical building (b) Flowchart of typical BD process for different building components

	BD PROCESS	Change Impact Level [LOW / MEDIUM / HIGH]
1	Designing Piles	LOW
2	Designing 1st Storey Slab	LOW
3	Designing 2nd Storey Beam, Column, Slab	MEDIUM
4	Designing 3rd Storey Beam Column, Slab	HIGH

	1	2	3	4
1	■	X	X	X
2	X	■	X	X
3		X	■	X
4			X	■

(c) BD Process DSM showing rework

Figure 3. BD Process DSM of a 4-storey building project

In addition, the Product DSM in the BD MDM does not differentiate between building components or contribute to rework and productivity analysis. This was observed when we previously modelled Product DSMs for the different building levels (i.e. level 2 beams, columns, slabs for the level 2 BD MDM and level 3 beams, columns, slab for the level 3 BD MDM), they looked identical. This is because the BD process repeats for each level in the building if they are the same type of structure (Refer to Figure 3 for illustration). Including the Product DSM in MDM will not add value/ give insights into the MDM analysis of each building level. Therefore, we removed the Product DSM for the Productivity MDM (see Figure 4).

However, we cannot ignore the information flow and process dependencies between the groups of building components if we wish to study the impact of rework and productivity of the entire building project. To do so, the user can refer to the BD Process DSM (Figure 3c), which represents the process dependencies between each group of building components, where each cell in the matrix represents the individual Productivity MDM of the respective group of building components. (i.e. Productivity MDM for Piling, Productivity MDM for 1st Storey, Productivity MDM for 2nd storey etc.)

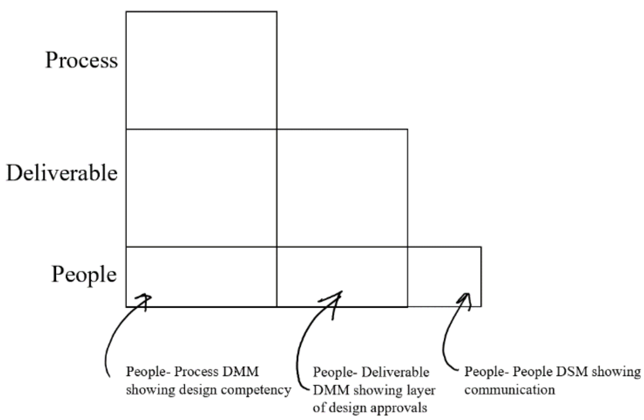
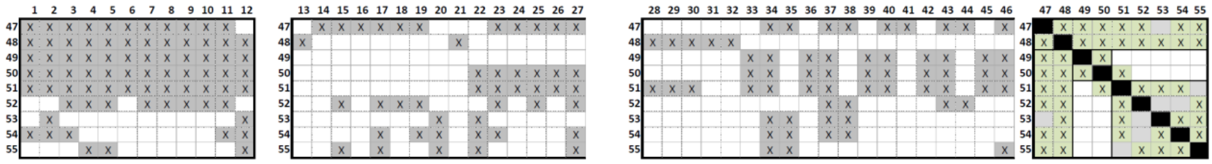


Figure 4. Schematic overview of Productivity MDM incorporated with designer productivity factors

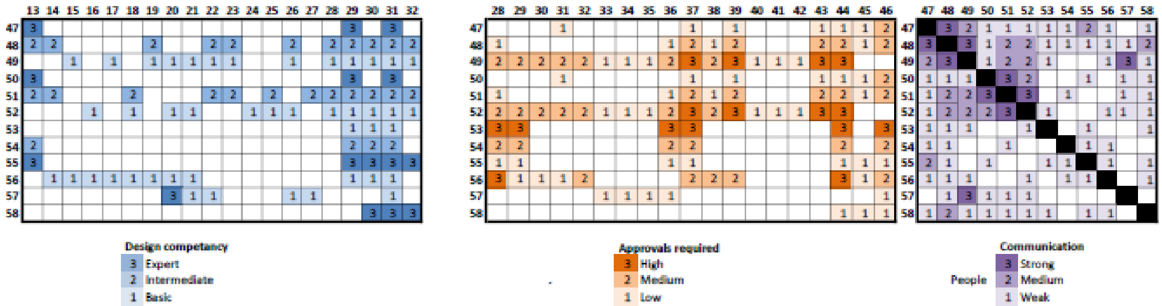
4.2 Analysis of Designer Productivity

As described in Section 2, rework impacts the BD process, significantly affecting a designer's productivity. Factors of designer's productivity in BD were consolidated from a previous qualitative study by the authors with experts in BD in Singapore and are described in the following sub-sections.

In the previous BD MDM, components in the People's domain only represent (single, uni-directional) dependencies to other domains, as seen in Figure 5a. To incorporate the factors of designer productivity, we now updated the respective matrices into figure 5b. The corresponding explanation of the components in the respective matrices is explained below.



(a) People Domain in BD MDM



(b) Updated People Domain in the Productivity MDM representing the design competency, layers of approvals, and strength of communication between designers respectively

Figure 5. Update of People's Domain matrices in Productivity MDM

4.2.1 Communication

Communication within and between design teams is one of the main factors in the designers' productivity. Communication of designers in the design process occurs in various interaction scenarios to achieve different purposes like handover, joint designing, and interface negotiations (Eckert et al., 2005). In a pilot study by the first author exploring factors of a designer's productivity in BD in Singapore, results show that company-level factors, including collaboration, communication, and information flow, are the most significant factors of a designer's productivity. The strength of communication is modelled in the organisation DSM (See figure 5b). We are especially interested in information flow interactions, which may be formal or informal peer-to-peer communications, including e-mail, face-to-face discussions, group meetings, presentations, file transfers, and so on (Eppinger and Browning, 2012), by three levels- high, medium, and low. We consider the frequency and quality of communication and represent the strength of communication in Table 1.

Table 1. Communication strength levels represented in the People-People DSM

Communication	Definition
High/ Strong	Information is transmitted accurately, clearly, and promptly resulting in the successful generation of solutions, ideas and decision-making.
Moderate	Information is transmitted adequately to generate ideas, solutions and make decisions.
Low/ Poor	Information is not transmitted clearly, promptly, or appropriately (Eppinger and Browning, 2012)

4.2.2 Design Competency

With increased design experience and competency, a structural engineer will have better judgement and skills to produce a structural design with fewer design errors. Reduced design errors in the process reduce the required time to identify and correct errors, improving designer productivity. Table 2 summarises the design competency levels in the People-Process DMM. The level of design competency is modelled in the DMM as shown in Figure 5b.

Table 2. Design competency level represented in the People-Process DMM

Design Competency	Definition
Expert	Experts can mentally stand back from the specifics of the accumulated examples and form more abstract conceptualisations pertinent to their domain of expertise (Cross, 2004).
Intermediate/ Experienced	Experienced designers make preliminary evaluations of their tentative decisions before implementing them and making a final evaluation. They consider whether it is worthwhile to move further into the implementation stage of a design decision. Experienced designers employ integrated design strategies (Cross, 2004).
Novice	Novices use 'trial and error' techniques to generate and implement design modifications, evaluate them, and generate another through many iterations(Cross, 2004).

4.2.3 3.2.3 Layers of Approvals

Interactions between designers may be based on relationships of authority, responsibility, accountability, and contractual obligations (Eppinger and Browning, 2012). For our case, we consider that the number of layers of approvals required for a designer to get their design and deliverables approved does not overlap with their design competency. For example, a competent engineer can produce accurate structural design quickly (high design competency) but will still require a set number of approvals from the senior designer and the qualified engineer. Hence, the layers of approvals depend on the hierarchy of the design team and the order the designer is in. Approvals affect the productivity of designers due to the increased time spent on correspondences and potential amendments. Table 3 summarises how the layers of approvals are represented in the People- Deliverables DMM and Figure 3b shows how it is modelled into the matrix.

Table 3. Layers of approvals represented in People- Deliverables DMM.

Layers of approvals	Definition
High	Design checks and approvals are required on all designs across departments and individuals.
Medium	Reporting relationships across departments to cross-check design, approval required for contractual obligations/ adhere to building regulations
Low	The designer makes decisions, and design does not require approval and minimal or no reporting relationships.

4.2.4 Technology Adoption and Availability

Technology adoption level refers to the tools and technology used for the structural design, which determines the type of documents used to communicate the design. These can be rule-of-thumb and back-of-envelope calculations in structural design, typically produced as sketches. Structural design software like RAPT and PROKON also produces design reports, PDFs, and CAD drawings. Higher-level structural 3D modelling and design software like Etabs and STAAD are also commercially available. Structural models and designs from this software are often produced as 3D Revit models. The design and drafting software used in structural design is paid licences which depend on a company's purchase and designer demand. This is reflected as a constraint of technology availability when performing specific design tasks. These above factors are modelled as attributes and are only process dependent.

In summary, the designer productivity of a process is the function of

- The availability of the technology (software licences) that is required for the process,
- The level of technology adopted in the process,
- The competency of the designers involved in the process,
- The level of communication between designers involved in the process,
- The layers of approvals required in the process.
- The amount of design changes required.

These qualitative factors were incorporated as elements or attributes into the respective domains in the MDM, as summarised in Figure 4.

5 Case study

A 60,000 sqm, 4-storey reinforced concrete building project in Singapore was used as a case study to collect data for the Productivity MDM. Two Productivity MDMs, representing each submission type, were collected and results presented in Figures 8 and 9. The individual Productivity MDMs can be used with the BD Process DSM shown in Figure 6 to understand the BD process of the entire building project.

	BD PROCESS	Change Impact Level [LOW / MEDIUM / HIGH]
1	Designing Piles	LOW
2	Designing Pilecap	LOW
3	Designing 1st Storey Slab	LOW
4	Designing 2nd Storey Beam, Column, Slab, Retaining w	MEDIUM
5	Designing 3rd Storey Beam Column, Slab	HIGH
6	Designing Underpass	LOW
7	Designing L1 Mezzanine Beam, Slab	LOW
8	Designing Steel Canopy	MEDIUM
9	Designing Steel Retail	MEDIUM
10	Designing Steel Entrance	MEDIUM
11	Designing 3rd Storey Beam, Column, Slab	HIGH

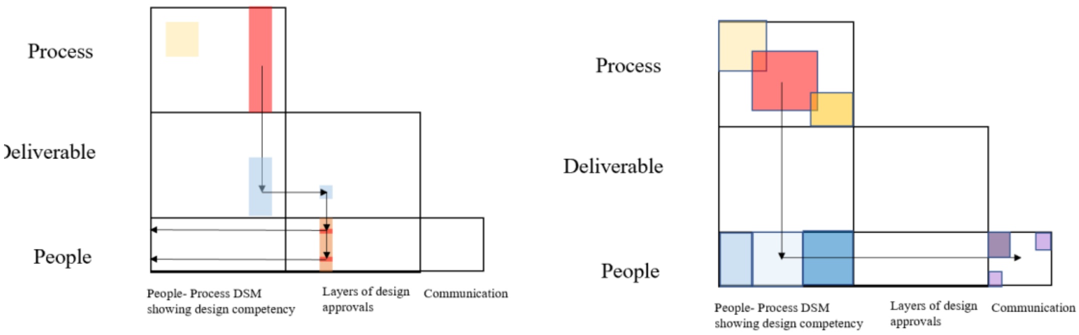
	1	2	3	4	5	6	7	8	9	10	11
1	■										
2	X	■									
3		X	■	X	X		X				
4				■	X			X	X		
5				X	■		X				
6						■					
7				X	X		■				
8								■			
9									■		
10										■	
11	X	X	X	X	X		X				■

Figure 6. BD Process DSM for case study building project

Problem analysis: Rework and designer productivity

Three rework loops are identified using the example of Level 3 Productivity MDM (Figure 8). Tracing the biggest rework loop in red (see Figure 7b), we can determine that fewer designers with high competencies are involved. Similarly, communication in these rework processes can also be improved. With this information, the BD process can be improved by increasing the resourcing of highly competent designers and improving communication in this critical area.

Using Productivity MDM Level 2 (Figure 9), the most critical processes within a rework loop are identified (Figure 7a). The corresponding dependent deliverables show a region of higher layers of approvals required. A possible process improvement is to reduce people, and that requires high layers of approvals forward in the BD process so the dependent deliverables will be closer to the diagonal, and the affected processes would occur in the smaller rework loop.



(a) Level 2

(b) Level 3

Figure 7. Productivity analysis using MDM

6 Conclusion and future work

The Productivity MDM proposed in this study incorporated significant designer productivity factors useful to manage the BD rework process and improve designer productivity. By modelling the BD rework process and designer productivity factors into the MDM, the mapping mechanism allows the user to use the different matrices to analyse the influences of one domain on another or to infer the presence of elements and relationships in one system from another (Eppinger and Browning, 2012). The information in the Productivity MDM offers opportunities for further numerical analysis to measure designer productivity. The Productivity MDM can also be adapted to other engineering processes prone to rework to provide an analysis of its impact on the designers.

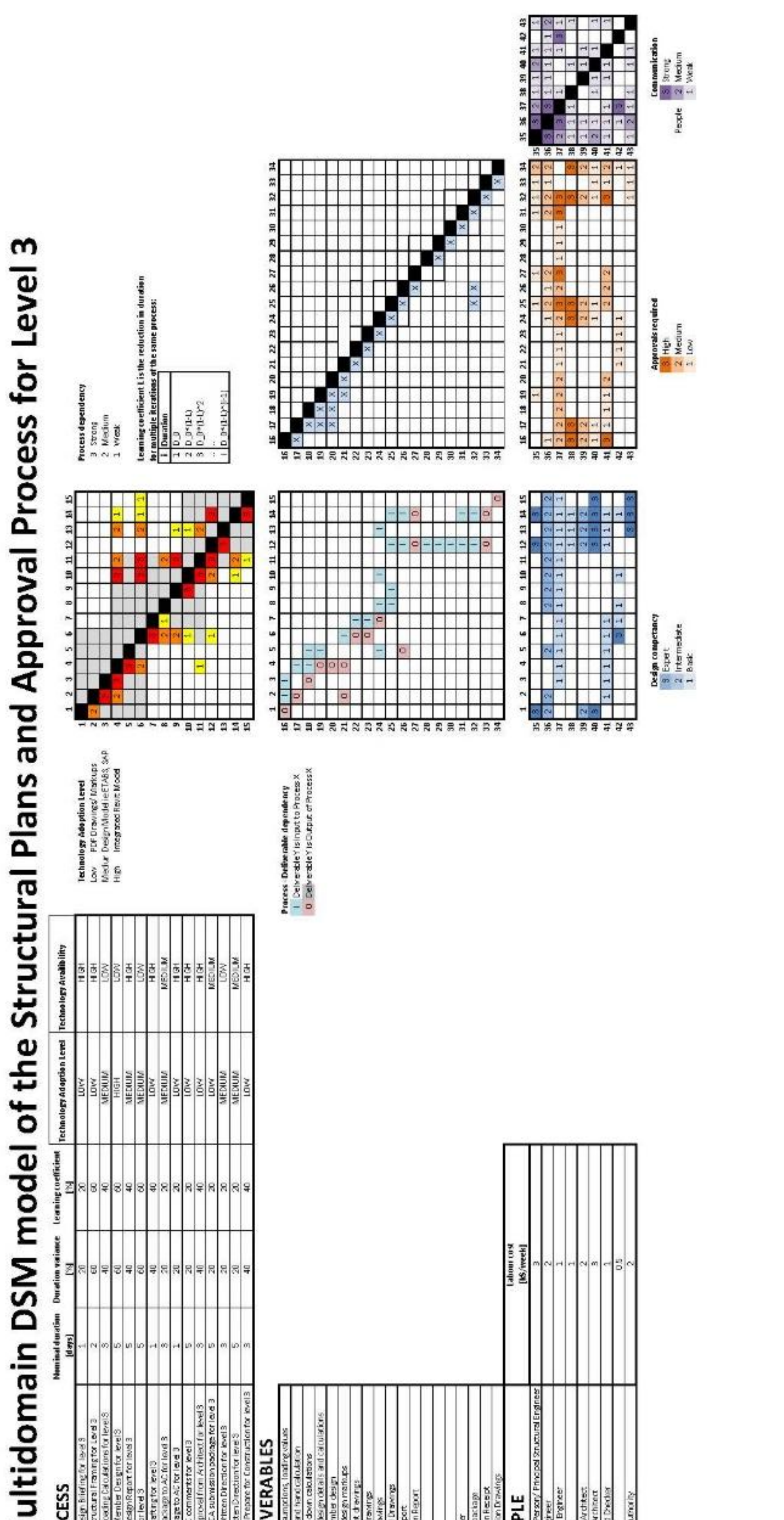


Figure 8. Productivity MDM for Level 3

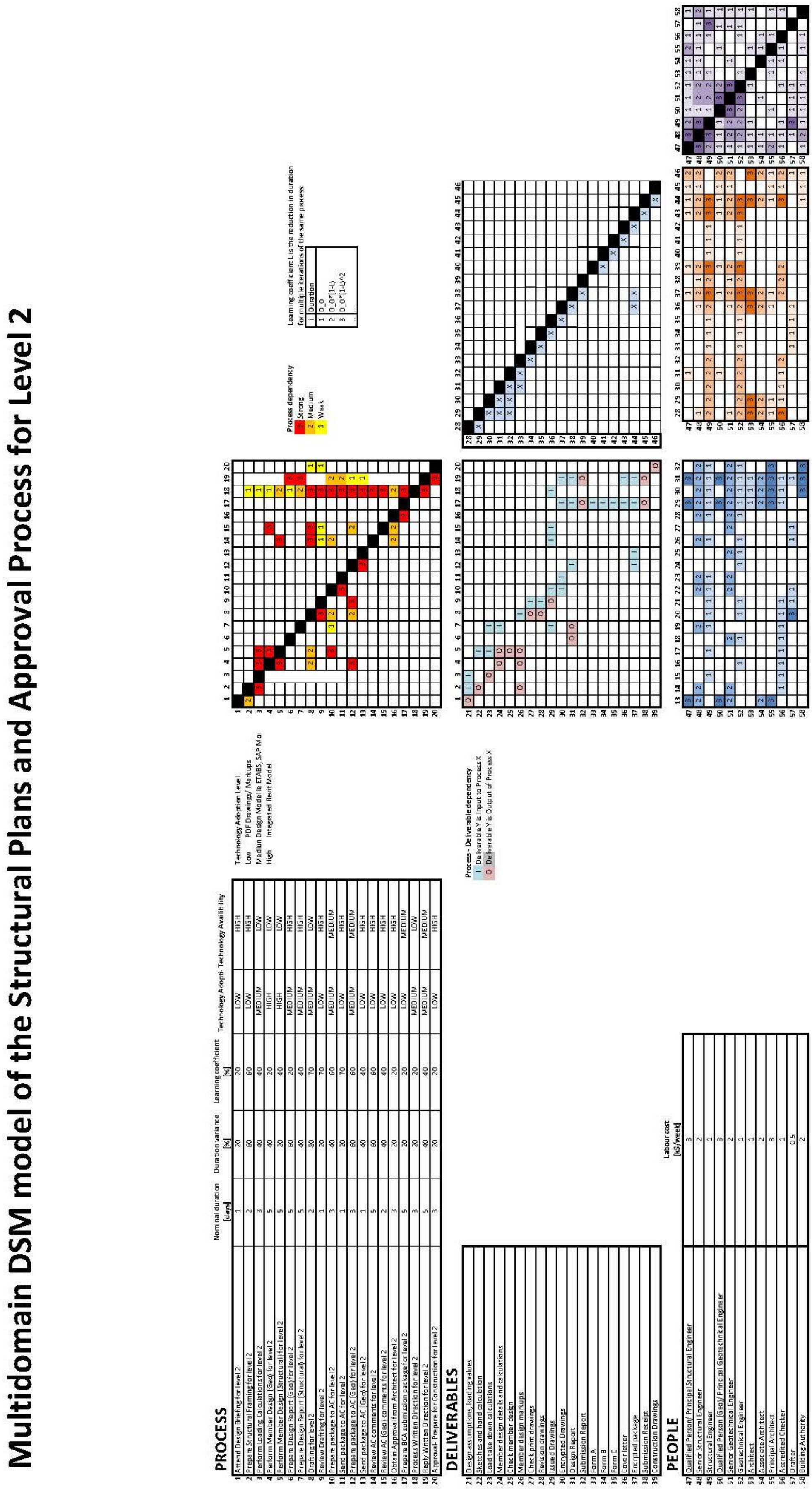


Figure 9. Productivity MDM for Level 2

References

Ahmad, N., Wynn, D. C. and Clarkson, P. J. (2011) "Information models used to manage engineering change: A Review of literature 2005-2010", in *DS 68-1: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 1: Design Processes, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011*,

Ahmad, N., Wynn, D. C. and Clarkson, P. J. (2012) "Change impact on a product and its redesign process: a tool for knowledge capture and reuse", *Research in Engineering Design*, 24(3), 219-244. 10.1007/s00163-012-0139-8

Cross, N. (2004) "Expertise in design: an overview", *Design Studies*, 25(5), 427-441

Eckert, C., Maier, A. and Mcmahon, C. (2005) "Communication in design", *Design Process Improvement: A review of current practice*, 232-261

Eppinger, S. D. and Browning, T. R. (2012) *Design structure matrix methods and applications*, MIT press. https://doi.org/10.7551/mitpress/8896.003.0003

Forcada, N., Gangolells, M., Casals, M. and Macarulla, M. (2017) "Factors affecting rework costs in construction", *Journal of Construction Engineering and Management*, 143(8), 04017032. https://doi.org/10.1061/(asce)co.1943-7862.0001324

Forcada, N., Rusiñol, G., Macarulla, M. and Love, P. E. (2014) "Rework in highway projects", *Journal of Civil Engineering and Management*, 20(4), 445-465. https://doi.org/10.3846/13923730.2014.893917

Gager, A. (2020) "Efficiency and Effectiveness: Know the Difference", *Journal of Business Management*, 234-235

Ma, G., Hao, K., Xiao, Y. and Zhu, T. (2019) "Critical chain design structure matrix method for construction project scheduling under rework scenarios", *Mathematical problems in engineering*, 2019,

Palaneeswaran, E. (2006) "Reducing rework to enhance project performance levels", in *Proceedings of the one day Seminar on" Recent Developments in Project Management in Hong Kong*,

Palaneeswaran, E., Kumaraswamy, M., Ng, T. and Love, P. (2006) "Neural network modeling for rework related cost overrun and contractual claims in construction projects", in *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, ICCCBE Montreal, 1393-1402

Tangen, S. (2002) "Understanding the concept of productivity", in *Proceedings of the 7th Asia-Pacific Industrial Engineering and Management Systems Conference, Taipei*, 18-20

Wong, Y. Y. B., Joyce, S. C. and Blessing, L. (2022) "Selecting Design Process Modelling Approaches for Building Design: A Review", *Proceedings of the Design Society*, 2, 71-80

Wong, Y. Y. B., Joyce, S. C. and Blessing, L. (2023) "Design Process Modelling to Measure Engineering Productivity in Building Design", *Proceedings of the Design Society*, 1, 201-210. https://doi.org/10.1017/pds.2021.21