Applying An Overlapped Design Schedule Based Dependency Structure Matrix to Minimize Project Makespan

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***Abstract*—Design process scheduling is conducted by optimizing human resources or workers allocation to several tasks in project with several real constraints to achieve the objective, minimizing the project makespan. In real business case, despite the tasks are already allocated to the optimal workers, rework still can happen because of the uncertainty. The rework can lead to unexpected extra time consumption. To anticipate this unexpected problem, tasks overlapping method is proposed in this research to reduce the project makespan after worker allocation. However the task overlapping method has a drawback, it requires more coordination and interaction between workers who conduct each of overlapping tasks. This research emphasize overlapped design schedule in a design process based on worker cluster from Dependency Structure Matrix (DSM). Worker DSM is used to encounter the task overlapping's drawback. Workers who come from same cluster have more coordination and interaction to each other. It is expected workers who assigned on tasks overlapped are from same cluster. This research's intention is to provide the workers allocation to obtain optimal project makespan result and create worker clustering from worker-DSM to identify the tasks that can be overlapped in design process. It is also expected to show the possible rework time from tasks overlapping's reduction time.**

Keywords— human resources allocation; project makespan; dependency structure matrix; worker cluster; overlapped design process; rework time

I. INTRODUCTION

The efficiency and effectiveness of the product development process need to be realized by reducing the time to market of their development effort [4]. Product development process duration time is very closely related with project scheduling, as a part of project management. Project scheduling's concern is commonly described as the allocation of limited resources to tasks over time [5]. The resources that required in project scheduling has many forms, such as budget, human, place, tools, etc. Human resources allocation becomes the most important and widely studied because it has more effects to project schedule and project cost compared to another resources, such as tools and machine [8]. In real business case, despite the tasks are already allocated to the optimal workers, rework still can happen because of the uncertainty. Therefore in order to achieve desired time-saving goals, overlapped process in process design is obtained [2]. The traditional method, an activity starts one its predecessor is completed. In overlapped activities concept successor begins earlier by using preliminary information from predecessor activity [11]. It makes overlapping activities requires more coordination and interaction between human resources who work on each activities that overlapped. This kind of interaction or communication pathways among those employees are captured by the marks or values in the matrix cells of Dependency Structure Matrix (DSM). Employees who have the greatest needs to communicate to each other will be located nearby the matrix, or it can be indicated as a group or cluster. It is one of the best to avoid the lack of natural communication facilitators [10]. According to those several references mentioned, there is not yet a research that combine human resources allocation method with overlapping activities method which considering organizational DSM. Moreover, if human resources allocation method is combined with overlapping activities, it can reduce more project makespan. Therefore because of several condition and reason mentioned above, an overlapped design schedule based DSM is proposed.

II. LITERATURE REVIEW

Overlapping of two tasks that have predecessor-successor (sequential) relationship is already being a fundamental strategy for time saving goals in project management. Tasks overlapped require communication and exchange of preliminary information more intensely and if it is not fulfilled can make their objective will be not achieved [2]. Terwiesch [11] explained that the degree to which dependent tasks may be overlapped is define by the nature of the information exchange, or commonly known as evolution (for predecessor) and sensitivity (for successor). The characteristics of these information in design task could evolve quickly or slowly and it can be modelled to estimate the time acceleration. Krishnan [6] applied it to the design process of an automobile door. However it is only specific for an information per a task. In real business case, there will be numerous tasks in a project or even more. Workers present as the agent of information delivery for every sequential tasks and worker is a limited resources. Therefore it comes an idea that it will be more effective and efficient if we model the workers. One of the method to model the worker is by clustering the workers based on their interaction strength using Dependency Structure Matrix (DSM) [13].

III. METHODOLOGY

A. Dependency Structure Matrix (DSM)

Dependency Structure Matrix or commonly known as Design Structure Matrix (DSM) is an information exchange model that allows the representation of complex task and/or worker relationships in order to determine a sensible sequence and/or grouping for the tasks and/or workers being modeled [9]. Information exchange among different teams within the organization is the crucial part of complex organizational system development. Furthermore according to Quashem [9] organization DSM could analyzes an organization, captures the structure of organizational units and designs it according to the communication flow among organizational units such as individuals (workers), teams, groups, departments, etc.

1) Sequencing Worker-DSM

The matrix concept of Worker-DSM is basically similar to Task-DSM. Task-DSM uses square matrix ($m \times m$) with the representation as a binary (1 or 0) or as weighted number (range value 0-1). It is a square adjacency matrix containing identical row and column captions. In case of worker-DSM, the row and column captions are the workers list. The binary or weighted number in matrix cells represent the dependencies or interaction weight between the workers. Yassine [14] already explained the steps to mapping the interactions on DSM.

The purpose of sequencing in worker-DSM is also similar to partitioning in task-DSM. It is to get the interactions as close to the leading diagonal, therefore there is more possibility to group the element or worker that has interaction together. Higher interaction weight value ($I_{k_{(i,j)}}$) becomes the priority to be as close to the leading diagonal. Equation (1) ensures that the higher $I_{k_{(i,j)}}$ located close to leading diagonal of DSM [13]. However to find which worker sequence will obtain the most minimum total value of interaction weight (TI_k), permutation concept will be applied to the initial worker sequence. Algorithm 1 will explain the computation of (1) within permutation method.

Minimize $$TI_k = \sum_{i=1}^{R} \sum_{j=i}^{R} (I_{k_{(i,j)}} \times |j - i|) \quad (1)$$

Algorithm 1. Sequencing Worker-DSM

Input: matrix of original worker-DSM (O); $I_{k(i,j)}$; $i \in R$; $j \in R$;

Procedure:
(1) Compute $K \leftarrow$ total number of permutation result for worker sequence; $k \in K$
(2) Compute $P \leftarrow$ set of permutation result that represents sequence of workers; $p \in P$
(3) $N \leftarrow 0$ {matrix of new worker-DSM}
(4) $TI_k \leftarrow \emptyset$
(5) Generate all the permutation result that represents sequence of workers (P)
(6) Transform matrix O into matrix N using p_k result
(7) Calculate TI_k froam each p_k
(8) Find p_k which has the most minimum TI_k

2) Clustering Worker-DSM

Worker Dependency Structure Matrix (Worker-DSM) is based on organization architecture DSM models. A powerful characteristic of worker DSM is it can capture not only the existence of an interaction, but also the interaction strength. There are two types of interactions [13]: (a) internal interaction based on internal dependencies between the worker elements within the cluster and represents the strength of the worker's interaction to each other in a cluster, and (b) external interaction based on external dependencies of the workers in the cluster with other workers outside the cluster and represents the strength of those workers' interactions. The focus of these function is towards identifying cluster the workers, from sequencing worker-DSM result, that have a maximum number of internal strength and a minimum number of external strength. By using this interaction strength, workers will be clustered. The objective of clustering is to find a group of workers that have higher value interaction strength and balance interactions become the cluster member together.

According to Whitfield [13], in order to have higher interaction strength of workers in a cluster, the internal strength of cluster ($S^c_{internal}$) need to be more than the external strength of cluster ($S^c_{external}$). Moreover it can be defined that the difference between $S^c_{internal}$ and $S^c_{external}$, it will called as strength indicator ($\mathcal{S}$), will be maximized and it becomes the objective function in worker-DSM clustering method, it can be referred to (2). The flowchart on Fig. 1, will be the decision maker to decide which workers that can be included as one cluster or not by following (2).

Maximize $$\mathcal{S} = S^c_{internal} - S^c_{external} \quad (2)$$

B. Worker Allocation

Resource management is crucial for the performance of an enterprise. One of the most important part of resource management is human resources assignment. The proposed human resources assignment method ranks the candidate employees and then selects the required worker for a task. The performance of a worker when executing a task in a project depends on various parameters such as the experience level, skills, time of the day etc. The higher the ranking of a worker, the more that worker demanded to finish the tasks. The resources that are required to perform tasks include personnel, usually described by numbers of hours, equipment, and facilities. Worker allocation to the task is required in order to get optimum project makespan. This research will emphasize the worker assignment based on task sequence.

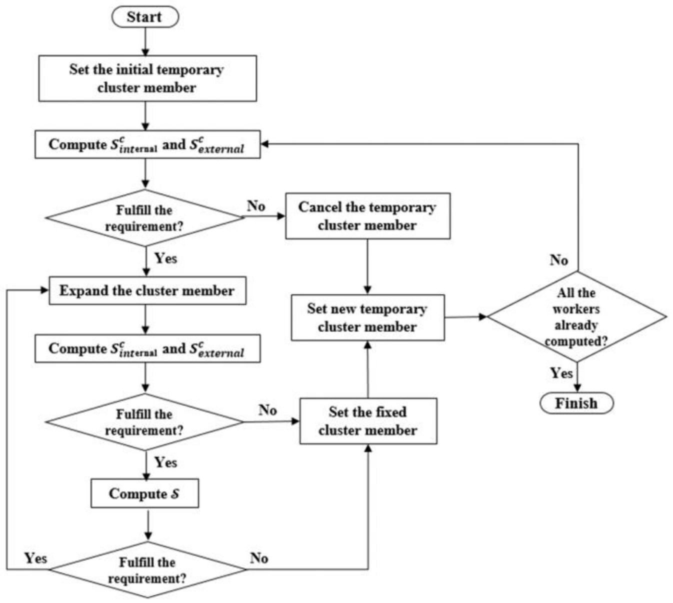

Fig. 1. Clustering flowchart.

Equation (3) shows the objective function to minimize project makespan (*TP*) by summed up the time of series set *s* ($t_{(\alpha_s)}$) and time of parallel set ℓ ($t_{(\beta_\ell)}$). The usage of series set and parallel set are in order to simplify the computational of *TP*. The clearer illustration of series set and parallel set can be found in Fig. 2. The ($t_{(\alpha_s)}$) has same value with its task's working time. To obtain ($t_{(\beta_\ell)}$) is by finding which task in parallel set ℓ that has the maximum working time. However, if in a parallel set there is a worker *r* finishes more than a task, then working time of those tasks will be summed up formerly. This concept creates a worker only can do one task at one time, because this way can avoid multitasking. Multitasking is not expected because it is one of project scheduling issues [12]. In the multitasking approach, one of the task or more will have interruption and this interruption will affect the working time.

Minimize $$TP = \sum_{\ell=1}^{L}\sum_{s=1}^{S}(t_{(\alpha_s)} + t_{(\beta_\ell)}) \quad (3)$$

Constraint (4) ensures that every task only has one worker that will be assigned. As lower the value of worker's working time (t_{rw}) is more desirable. Constraint (5) ensures that every workers will not consumes their working time more than their average of total working time ($\bar{T}_r$) to finish the assigned task. One of the constraints is workload balancing among workers is vital to ensure fairness and employee convenience [3]. Therefore, even though there is a worker who always can finish the task faster than others, that worker will not do all of the tasks. Variable X_{rw} determines which worker *r* will finish which task *w*.

$$\sum_{r=1}^{R} X_{rw} = 1 \quad (4)$$

$$\sum_{w=1}^{W}(t_{rw} \times X_{rw}) \leq \bar{T}_r \quad (5)$$

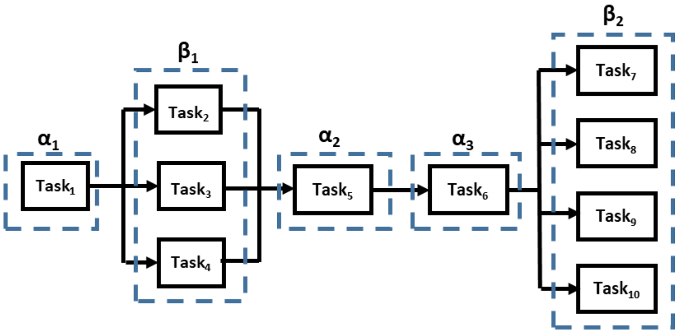

Fig. 2. Illustration of series set and parallel set in task flow.

The traditional methods to deal with project makespan in project management are known as PERT, GERT, and CPM. However neither those methods consider the various human resources constraints [7]. Therefore to achieve this objective, one of trusted technique which is usually used is Genetic Algorithms. Human resources allocation is a combinatorial and NP hard problem, therefore Genetic Algorithms is more suitable to use to solve its problem. The several researches confirms that Genetic Algorithms can be used for large scale assignment, planning and rescheduling problems since they have shown to be suitable in solving these problems efficiently [15].

Fitness value will be obtained from fitness function and basically fitness function is the objective function from the mathematical model, or it can refer to (3). If there is a chromosome that cannot fulfill the constraints, that chromosome will be not selected to be parents for next step. The chromosome's bit structure for assignment problem is unique. According to Banerjee [1], a chromosome will consist of task-bit and every task-bit will consist of worker-bit. To prevent invisible solutions in child or next generation, the requirement of bit cross over point is modified. Task-bit is chosen as cross over point and mutation point.

C. Overlapped Design Process

The optimum project makespan is already obtained, however the project makespan still could be minimized by identifying which tasks that can be overlapped. The basic requirements of overlapped design process is the two tasks need to be in a pair of predecessor and successor task. If those tasks do not have any task precedence relationship, they will be canceled as a candidate of overlapping task. Second basic requirement is the worker of predecessor task and the worker of successor task need to be from same cluster. Therefore the worker of predecessor task can deliver the preliminary information more easily to the worker of successor task without they require to have more coordination or interaction intensely. Next, the worker of predecessor task must not be same with worker of successor task. It is in order to avoid multitasking in workers [12]. Fig. 3, shows the research framework of overlapped design process.

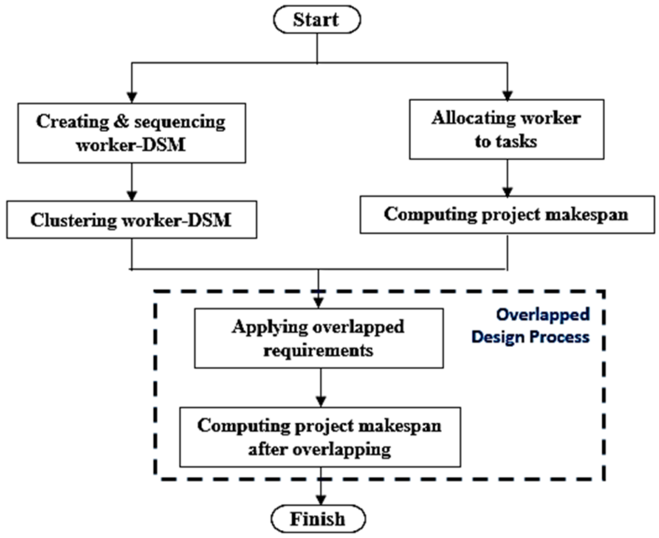

Fig. 3. Research framework of overlapped design process.

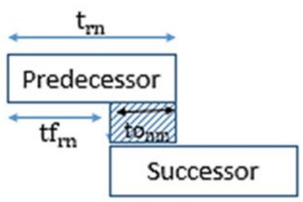

Fig. 4. The concept of overlapping time.

Equation (6) describes the computational of final project makespan after overlapping is applied. This objective function is the subtraction of overlapping time (to_{nm}) from the project makespan (TP). Variable O_{nm} is a decision variable that determines which predecessor task and successor task that can be overlapped according to the overlapped requirements. The concept of overlapping task is depicted on Fig. 4. Overlapping time can be obtained by the subtraction of the earlier time (tf_{rn}) from the predecessor working time (t_{rn}). This earlier time indicates the time when predecessor starts to deliver the preliminary information to successor [6]. If there the predecessor task comes from parallel set, the predecessor need to be chosen by the task that has maximum working time. The way is held because the successor task need to be guaranteed that also has got all information from other task in the same parallel set. Afterwards, if the successor task is included in a parallel set, the successor will be chosen by the one which has the maximum working time (M_n).

$$\textit{Minimize} \quad TP_{overlap} = TP - \sum_{m=1}^{|M_n|} \sum_{n=1}^{W} to_{nm} \times O_{nm} \qquad (6)$$

IV. Result

The research case study is taken from a Taiwanese company's design process. The company is engaged in the aerial vehicle, especially in Unmanned Aerial Vehicle (UAV) for Taiwan military. The specific product for this design process is the wheel for UAV. The design process has 41 tasks and 9 workers. Each worker has their own skill, it means that the worker has several tasks that they can conduct. It makes each task has worker candidate whom also differentiate by the worker's working time.

A. Worker Sequence in Worker-DSM

TABLE I. Worker Sequence Result

Index of Set Permutation (k)	Worker Sequence	TI_k
1	A – B – C – D – E – F – G – H – I	81,2
…	…	…
153902	F – B – D – H – C – I – E – A – G	95.2
…	…	…
246215	**I – E – D – F – G – A – B – H – C**	**61.8**

The worker sequence that obtained from the minimum TI_k value from the permutation result is I – E – D – F – G – A – B – H – C. It implies that the worker who has least interaction with other workers is worker I and worker C because they are located on the edge of matrix. Worker who has most interaction with other workers, worker F and G, are located in the middle of matrix and the highest interaction weight located close to the leading diagonal. The worker sequence of the minimum TI_k value will help clustering process easier later. Table I shows the worker sequence from each index of set permutation (k) and the TI_k value from each worker sequence.

B. Worker Clusters

The clustering method gives result 3 clusters with one of the cluster has four members inside and the rest of clusters have three members. The first cluster's member is worker E, worker D, worker F, and worker G. Second cluster's member is worker G, worker A, and worker B. the last cluster's member is worker B, worker H, and worker C. Fig. 5, depicts the clustering result of worker-DSM. Fig. 5, implies that between workers in a pair which in same cluster has interaction weight is quite high and less gap of interaction weight. Interaction weight between pairs of worker in same cluster also has gap value which is not so high to each other. These conditions create those workers can be clustered together and generate higher internal strength, furthermore they can balance their interaction to each other.

	I	E	D	F	G	A	B	H	C
I		0.067	0.067	0.467	0.2	0.2	0.2	0.267	0.067
E	0.067		0.4	0.6	0.467	0.333	0.333	0.133	0.2
D	0.067	0.4		0.667	0.533	0.333	0.333	0.133	0.2
F	0.2	0.467	0.533		0.8	0.533	0.467	0.2	0.333
G	0.133	0.4	0.533	1		0.6	0.533	0.2	0.333
A	0.067	0.133	0.2	0.733	0.733		0.533	0.467	0.467
B	0.067	0.133	0.2	0.733	0.733	0.467		0.467	0.533
H	0	0.133	0.067	0.467	0.4	0.333	0.333		0.067
C	0.067	0.133	0.133	0.2	0.2	0.267	0.267	0.267	

Fig. 5. Clusters result in worker-DSM.

C. Worker Allocation and Project Makespan

Each task in this project needs to be allocated to only one worker, therefore each task will has their own duration time based on working time which is from the allocated worker. By using Genetic Algorithms to allocate the workers and obtain the project makespan, there are several parameters need to be set first. There are crossover rate and mutation rate. The most optimum project makespan is obtained from crossover rate value is 0.08 and mutation rate value is 0.01. This parameters can reduce the variation in the result. Taguchi method is used to select the optimum parameters. This parameters gives 2 solutions of worker allocation. Those 2 solutions come from the generation in genetic algorithm. These generations give the same minimum result of project makespan which is 301 days. Each of generation gives different chromosome. Different chromosome means that the worker allocation combination also different. However, this different worker allocation will affect to the next step, task overlapping execution.

D. Overlapped Design Process Result

The worker clusters, worker allocation combination, and project makespan result is already obtained. According to the overlapped design process, the project makespan can be compressed again and because there are 2 solutions, the most minimum project makespan after this overlapping method could be identified. Solution 1 gives 9 pairs of predecessor & successor tasks that can be overlapped. Then there are 7 pairs of predecessor & successor tasks that can be overlapped that obtained from Solution 2. The complete overlapped design process result with the workers allocation and overlapping time for Solution 1 can be seen on Table II and Table III is for Solution 2. Furtehrmore, Solution 1 creates the project makespan after overlapping ($TP_{overlap}$) become 252 days. Then the project makespan after overlapping ($TP_{overlap}$) become 276 days for solution 2.

According to Table II and Table III, Solution 1 will gives the most minimum result in project makespan. The overlapping time from overlapped design process method creates the project makespan is more minimized and this reduction time could be used as rework time, if in real execution the project need to be rework (uncertainty) and this project will not be delayed. The illustration of the project makespan result before and after overlap with the rework allocation time can be checked on Fig. 6. Rework allocation time for Solution 1 is 49 days and rework allocation for Solution 2 is 25 days.

TABLE II. OVERLAPPED DESIGN PROCESS RESULT FROM SOLUTION 1

Overlapping Location		Worker	Cluster	to_{nm}
Predecessor	**Successor**			**(days)**
P8	Q2	G and B	2nd	6
R3 and R4	R5	D, E, and G	1st	6
R5	S1	G and E	1st	20
S1	R6	F and D	1st	2
R6	R7	D and E	1st	5
R7	R9	E and F	1st	2
T4	S6	B and A	2nd	4
S6	T5	A and G	2nd	2
T6	T7	G and A	2nd	2
Total to_{nm}				**49 days**

TABLE III. OVERLAPPED DESIGN PROCESS RESULT FROM SOLUTION 2

Overlapping Location		Worker	Cluster	to_{nm}
Predecessor	**Successor**			**(days)**
P4	P5	A and B	2nd	5
P5	P6	B and H	3rd	2
P8	Q2, Q5	G and B, F	1st (G & F) 2nd (G & B)	6
R3 and R4	R5	D, E, and F	1st	6
S1	R6	F and E	1st	2
R7	R9	E and F	1st	2
S6	T5	A and G	2nd	2
Total to_{nm}				**25 days**

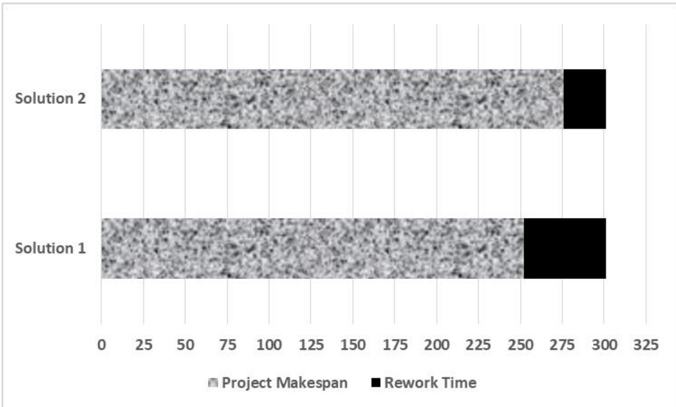

Fig. 6. Project makespan after overlapped.

V. CONCLUSION

This research emphasizes overlapped design schedule in a design process in a Taiwanese UAV company. There are 41 tasks need to be assigned to a worker optimally. The total workers who will be involved is 9 workers. In previous research to apply the overlapped design method, the information exchange characteristics of each sequential task is modelled. However, in most cases the number of tasks is more than the number of workers. Therefore, this research approaches the overlapped method from the workers' interaction. Since worker cluster could represent the workers' interaction, worker cluster can help to conduct overlapped design process because this method requires more interaction between workers whose tasks are overlapped. Dependency Structure Matrix (DSM) is used to conduct worker clustering. The algorithm to conduct the clustering in worker-DSM is also provided in this research. It is identified that 8 out of 9 workers are clustered into 3 worker clusters.

Those workers will be assigned to the tasks by considering the task sequential type (series and parallel) and worker's skill on each task. This assignment problem is solved by using Genetic Algorithms. The optimum project makespan is 301 days. Moreover, by using overlapped design, the project makespan could be minimized up to 16%. This reduction time comes from 9 pairs of sequential tasks which can be overlapped. In previous research, worker assignment and design overlapped process were discussed separately, even though both of them are part of project management and both of them have significant effect to project makespan.

Furthermore, this research topic needs improvements which could make the result is more effective, efficient, and the factor condition is closer to the real business. In business case multitasking is hard to be avoided, therefore considering multitasking to the workers need to be applied. In operation research point of view, using different meta-heuristic method, such as discrete Genetic Algorithm, need to be applied. It is in order to compare the result then the meta-heuristic method which gives more optimum result could be identified and applied.

REFERENCES

[1] Banerjee, Nilanjan, Vaibhav Mehta, and Sugam Pandey. "A genetic algorithm approach for solving the routing and wavelength assignment problem in WDM networks." In *3rd IEEE/IEE international conference on networking, ICN*, pp. 70-78. 2004.

[2] Bogus, Susan M., Keith R. Molenaar, and James E. Diekmann. "Concurrent engineering approach to reducing design delivery time." *Journal of construction engineering and management* 131, no. 11 (2005): 1179-1185.

[3] Cabanillas, Cristina, José María García, Manuel Resinas, David Ruiz, Jan Mendling, and Antonio Ruiz-Cortés. "Priority-based human resource allocation in business processes." In *International Conference on Service-Oriented Computing*, pp. 374-388. Springer, Berlin, Heidelberg, 2013.

[4] Carrascosa, Maria, Steven D. Eppinger, and Daniel E. Whitney. "Using the design structure matrix to estimate product development time." In *Proceedings of the ASME design engineering technical conferences (design automation conference)*, pp. 1-10. 1998.

[5] Herroelen, Willy, Erik Demeulemeester, and Bert De Reyck. "A classification scheme for project scheduling." In *Project scheduling*, pp. 1-26. Springer US, 1999.

[6] Krishnan, Viswanathan, Steven D. Eppinger, and Daniel E. Whitney. "A model-based framework to overlap product development activities." *Management science* 43, no. 4 (1997): 437-451.

[7] Li, Haitao. "A Rollout Algorithm for the Resource-Constrained Project Scheduling Problem with Stochastic Task Durations." *University of Missouri, Project Final Report* (2011).

[8] Maenhout, Broos, and Mario Vanhoucke. "An exact algorithm for an integrated project staffing problem with a homogeneous workforce." *Journal of Scheduling* 19, no. 2 (2016): 107-133.

[9] Quashem, Rumana. "Design structure matrix: Models, applications and data exchange format." PhD diss., University of Lethbridge (Canada), 2015.

[10] Sosa, Manuel E., Steven D. Eppinger, and Craig M. Rowles. “Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions.” Journal of Mechanical Design 125 (2):240-252. 2003.

[11] Terwiesch, Christian, and Christoph H. Loch. "Measuring the effectiveness of overlapping development activities." *Management science* 45, no. 4 (1999): 455-465.

[12] Weydt, Ingunn Kristine. "The human side of project management: an investigation of critical chain concepts in the Argentinean Project Environment." PhD diss., 2008.

[13] Whitfield, Robert I., Joanne S. Smith, and Alex B. Duffy. "Identifying component modules." In *Artificial Intelligence in Design’02*, pp. 571-592. Springer Netherlands, 2002.

[14] Yassine, A. "An introduction to modeling and analyzing complex product development processes using the design structure matrix (DSM) method." *Urbana* 51, no. 9 (2004): 1-17.

[15] Younas, Irfan. "Using Genetic Algorithms for Large Scale Optimizationof Assignment, Planning and Rescheduling Problems." PhD diss., KTH Royal Institute of Technology, 2014.