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AN AGENT-BASED APPROACH TO MODELING INTEGRATED PRODUCT TEAMS UNDERTAKING A DESIGN ACTIVITY

Yee-Wai Sim
Richard Crowder
School of Electronics and Computer Science
University of Southampton
Southampton, UK
{rmc, yws01}@ecs.soton.ac.uk

Mark Robinson
Helen Hughes
Leeds University Business School
University of Leeds
Leeds, UK
m.robinson@lubs.leeds.ac.uk
h.hughes@leeds.ac.uk

ABSTRACT

The interactions between individual designers, within integrated product teams, and the nature of design tasks, all have a significant impact upon how well a design task can be performed, and hence the quality of the resultant product and the time in which it can be delivered. In this paper we describe an ongoing research project which aims to model integrated product teams through the use of multi-agent systems. We first describe the background and rationale for our work, and then present our initial computational model and results from the simulation of an integrated product team. The paper concludes with a discussion of how the model will evolve to improve the accuracy of the simulation.

INTRODUCTION

It has become common practice for many organizations to form multi-disciplinary *Integrated Product Teams* (IPTs) as a result of supporting the move to concurrent engineering practices [24]. However, to succeed in performing a design task, the organization depends not only on the technology employed and the attributes of the individual designers (e.g. technical competency and motivation); but also on the interactions (e.g. collaboration, communication and cooperation) between individuals and with their organizational environment, as suggested by socio-technical systems theory [11]. Furthermore, commercial pressure is increasing to address the paradoxical need for robust systems, which are insensitive to variation in their manufacture and operating environments, whilst also having the high levels of performance and innovation essential for competitiveness. In view of this, modeling and simulation of the engineering design process within IPTs may help address this paradox.

A design process tends to involve a large amount of innovation, creativity, concurrency and iteration [19]. Ambiguities, uncertainties, and interdependencies among activities, their results, human resources, and their tools make the design process complex and challenging to model. However, Browning and Ramasesh [6] identified two fundamental propositions that provide support and motivation for developing design process models. Firstly, the engineering design process exhibits repeatable structure, [1][32], and consistent patterns [27]. This means when a new design problem emerges, an individual or organization tends to follow a similar approach and learns through successive instances. Secondly, a design process is facilitated by a structured approach, i.e. a process model, which underlies most project management literature (e.g. [21][29]). Such an approach becomes especially important as the information flows become more complex in product design and development projects.

Agent technology has much to offer in understanding the interactions within IPTs when performing design tasks. The challenge is to explore the extent to which agent technology can be used to help understand, model, simulate and compare alternative ways of working, thereby supporting decision-making when constructing or revising IPTs. It is recognized that using multi-agent systems to model social systems within organizations is considered to be constructive approach. Jennings [18] identify the key characteristics of multi-agent systems, in that each agent has incomplete information or capabilities for solving the problem, there is no global control, data is decentralized, and computation is asynchronous. These are the very circumstances that usually apply to people in large organizations. Multi-agent systems are therefore potentially both a metaphor for the behavior of humans in organizations, and a method for studying them. Indeed Luck, McBurney and Priest [20] argue that "….multi-agent systems offer strong models for representing real-world environments with an appropriate degree of complexity and dynamism…". A multi-agent system not only facilitates the analysis of the resultant team dynamics, but also allows the authors to investigate the applicability of agent-theoretic approaches in this research work.

In the following sections of this paper, we describe our approach to developing a computational model of an IPT and the associated design process from a socio-technical viewpoint, as opposed to the modeling approach taken by the iterative design process [36], and the simulation based on these models. It should be noted that our approach will not yield absolute information (e.g. number of hours taken to complete a task), but rather investigates the sensitivity to variation in the design process and IPTs (e.g. revising the composition of a team or communication policies). Finally we present the initial results obtained from simulating a number of typical engineering design scenarios, and conclude by discussing the challenges associated with the development and validation of the computational model.

RELATED WORK

Team working offers many benefits and advantages over individual working in terms of improving organizational efficiency and quality [1]. In view of this, team working has been extensively studied by researchers in the field of psychology, who have examined team interactions and resultant performance (e.g. [14], [16], [34] [35]). There is widespread acceptance that team working must be cultivated by organizations in order to achieve effectiveness and efficiency [14]. A team's performance also depends on the characteristics of its individual members (e.g., motivation and ability) [17] [23].

Communication in team working is a crucial factor in determining the efficiency and effectiveness of a design activity [16]. Furthermore, the work reported by Patrashkova-Volzdoska et al. [28] and our own research suggests that communication plays an even more important role in IPTs compared to conventional work teams. This is due to the multi-disciplinary nature of the IPTs, as they are composed of individuals from a number of diverse technical and non-technical backgrounds [12]. Furthermore, it is widely recognized that engineering design involves situations of distributed cognition, such that the knowledge required to achieve particular objectives is distributed among several people, thereby necessitating communication [7]. Communication structure has also been studied, largely in the context of communication networks, or social networks, which refer to the "pattern of open channels of communication, or informal exchange, between members of a particular group" [25].

Although psychology research has made a significant impact on our understanding of team working, it has tended to take a social perspective, and neglected the impact of structural team factors, such as those related to the nature of the design task itself. As such, it might be considered that the psychological literature fails to consider the technical aspects of socio-technical systems theory [11], where both the social and technical elements are crucial for a design task to be performed successfully.

Several approaches to modeling and simulating engineering design teams and IPTs have been reported in the literature to date. For example, the GRAI-Engineering approach models the structure of the coordinated decision and design activities, and is based on systems, hierarchy and activity theory [13]; while O'Donnell and Duffy proposed a version of the IDEFØ model to measure team performance, which relates efficiency to effectiveness [26]. However, neither of these modeling approaches considers social interactions among team members. A simulation tool named TEAKS [22] was reported to take a multi-agent system approach to modeling the human social interaction and behavior in a team. However it does not focus on the technical aspects of design activities. Finally, research conducted by Tsvetovat and Carley employed multi-agent simulation methods to model complex socio-technical systems [33], but their results did not include the explicit elements [26] used in measuring team performance.

INTEGRATED PRODUCT TEAM MODEL

We approach the modeling of workflow by dividing a design activity or task into a number of sub-tasks, each of which will be undertaken by a single designer. Considering the design activity shown in Figure 1, the workflow rules can be expressed as follows:

- All sub-tasks can be performed simultaneously or sequentially. For instance, *Sub-task 2* and *Sub-task 4* can be executed in parallel with *Sub-task 3*. This is to support the concurrent engineering practice, which is a common practice in many organizations nowadays.
- A sub-task can only start if the ones preceding it are completed (except sub-tasks that are at the start of the design task). For example, *Sub-task 2* and *Sub-task 3* can only start after *Sub-task 1* is completed; while *Sub-task 5* can only commence after *Sub-task 3* and *Sub-task 4* are both completed.
- Each designer can only carry out one sub-task at a time. This means that, if *Sub-task 2* and *Sub-task 3* started at the same time, Designer 3 would have to work on these sub-tasks in sequential order instead of simultaneously.
- The priority of task execution is determined by the sub-task index number, where the smaller index numbers have a higher priority compared to the bigger ones. As an example, *Sub-task 2* and *Sub-task 3* are both assigned to *Designer 3*; so, if both these sub-tasks

have the same start time, *Sub-task 2* will be executed before *Sub-task 3*.

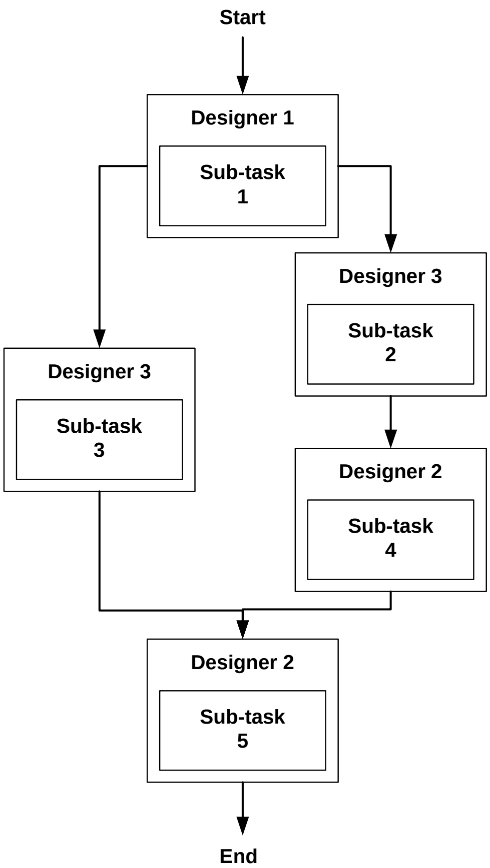


Figure 1: A typical workflow of a design activity being undertaken by three designers

As a result of reviewing previous research in the fields of psychology, computer modeling and engineering, a set of key independent variables that characterize an engineering design environment were identified. These variables were divided into three levels: *individual* (i.e. competency, motivation also termed goal-commitment, and availability), *team* (i.e. communication), and *task* (i.e. problem solving demand). In addition, a set of dependent variables, namely *time*, *cost* and *quality* were also identified. According to Atkinson, these variables are typically referred to as the iron triangle in project management research literature [1]. It should be noted, however, that the model is still under development, and further team-level variables – such as shared mental models and trust – will be incorporated into future versions as the work progresses. This future work will serve to further develop the interactions between the various agents, thereby more realistically representing team working.

Fieldwork is being undertaken to develop the model using real world data from IPTs operating within two multi-national engineering organizations. A theoretical framework was employed in the modeling process, which hypothesized relationships between the identified variables. Using the preliminary fieldwork findings, the relationships between the independent and dependent variables were constructed based on statistical multiple regression analyses. In accordance with hypotheses derived from existing psychological theory, complex three-way moderated relationships [10] between the three independent variables and each dependent variable were tested. However, no such moderated relationships were found; rather, simple regression equations provided the best fit to the data and were therefore used to inform the model. In simple terms, the relationships were formulated as:

$$T = f(P_{ST}, C_D, M_D) \quad (1)$$

$$Q = f(P_{ST}, C_D, M_D) \quad (2)$$

where

- T is the time for the designer to complete the sub-task.
- Q is the quality of the completed sub-task.
- P_{ST} is the sub-task's problem solving demand
- C_D is the individual designer's competency
- M_D is the individual designer's motivation

The overall cost in completing a specific design task, can be calculated by multiplying the fixed and variable overhead cost for a specific designer with the time to complete all the allocated sub-tasks. It should also be noted that quality (*Q)* is actually a metric that reflects a comparison between the actual and intended outcomes of all the work during the course of a design activity.

The model of an individual designer undertaking a specific design sub-task was developed based on the preliminary fieldwork findings and IDEFØ modeling approach [8]. IDEFØ supports the modeling of activities in organizations and their inter-relations. However, it is non-temporal and does not represent the performance elements (e.g. cost and quality) explicitly [26] for analysis purposes. Hence, we modified the IDEFØ modeling method to include the temporal element, performance metrics, and social aspects. This will enable the development of a model (depicted in Figure 2) that can be used in building a multi-agent system.

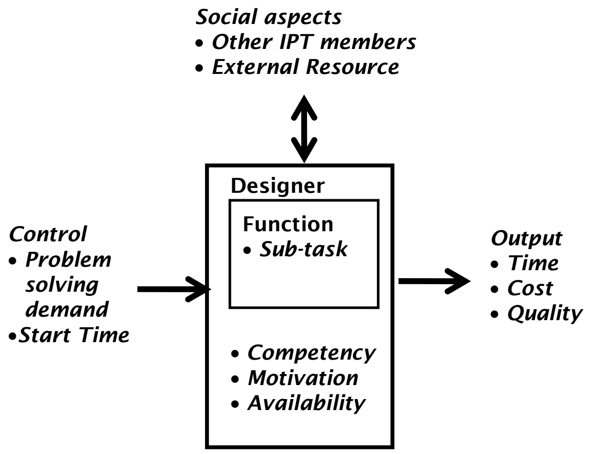


Figure 2: The model of an individual designer undertaking a specific design sub-task

In a typical IDEFØ model, a function uses a mechanism to convert input to output under the constraint of control. However, since the mechanism (personnel who perform the function) in our model is the designer, we grouped it with input as one entity. This modeling method will match more closely to our agent-based approach. The variables that we have currently incorporated into the model are summarized in Table 1.

Table 1: Summary of variables used in the current version of the model.

Variable	*Description*
Problem solving demand	The sub–task's requirements, including its complexity and other requirements; currently these are combined into a single variable.
Competency	A single variable comprising all of the designer's individual attributes that are causally related to high performance in a given task, such as technical ability.
Motivation	The designer's commitment in achieving the set goal
Availability	The designer's allocated time spent on the design sub-task as a proportion of his/her working time in the organization

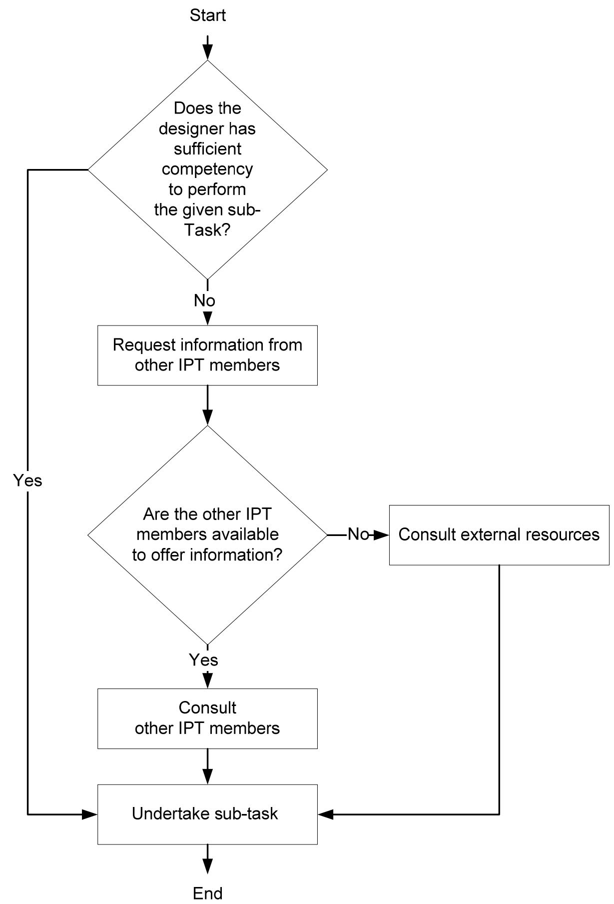


Figure 3: A simplified flow diagram of the current communication rules

The currently implemented communication rules, as illustrated in

Figure 3, were devised so that a designer with insufficient knowledge (express as competency in our model) to complete a sub-task can request information from a range of sources, i.e. other IPT members or external resources. Currently, the response rate of each designer to a request varies according to their competency level. A designer with higher competency level will typically have a lower response rate compared to those with lower competency. Based on the communication rules, the time taken to acquire the required knowledge (T_l) is calculated using:

$$T_l = \frac{f(C_r, P_{ST})}{\sum_n f(C_r, C_{res})} \quad (3)$$

where

- C_r is the competency of the individual designer requesting information
- C_{res} is the competency of the individual designer responding to the request

- P_{ST} is the sub-task's problem solving demand
- *n* is the number of designers who responded to the information request

The equation assumes that more knowledge transfer will take place if the competency gap between the designer requesting information and the one responding is larger and positive (i.e., the responding designer has a higher competency level). Furthermore, it also assumes that T_I will be shorten if more IPT members respond to the request. It is important to recognize that such knowledge transfer serves to increase the competency level of the recipient designer agents. Consequently, the competency level of designer agents receiving such information will increase throughout a simulation run, thereby mimicking the learning that takes place in real engineering environments.

Therefore if a designer goes away and requests information, the time taken to complete a sub-task will be $T+T_I$. However in practice, designers do not spent 100% of their available working time undertaking a single sub-task. In view of this, we incorporated an availability variable (see Table 1), which will modify the sub-task completion time, providing us with a more realistic figure. Hence the total time T_{tot} to complete a given sub-task is given by:

$$T_{tot} = \frac{T + T_I}{a} \quad (4)$$

where *a* is the availability and lies between 1 and 0.

Balancing the relative importance of the identified key variables employed in the model, and their inter-relationship, is fundamental in developing a realistic simulation. Given the difficulty of accurately quantifying such variables, our initial approach is to use a finite, qualitative set of semantic descriptors: *very low*, *low*, *medium*, *high, and very high*. The weightings for each of the variables will be adjusted based on the analyzed data obtained from the current ongoing fieldwork, together with detailed discussions with our industrial partners.

Finally, we have constructed our model in a bottom-up manner, such that the work of the individual designer agents was first addressed, before gradually incorporating further agents and inter-agent communication, with a view to ultimately representing team working. While the current model has now fully incorporated the work of individual designer agents, we are still developing those aspects of the model that address social interaction and communication between the agents, and this is now the main focus of our ongoing research.

ORGANIZATIONAL RESEARCH

Following a review of previous research in the fields of psychology, computer modeling and engineering, as discussed earlier in the paper, we identified key independent variables at three levels: *individual* (e.g. competence, goal commitment); *team* (e.g. communication, shared mental models, trust); *task* (e.g. problem solving demand). Furthermore, dependent variables including time and quality were also identified. Given the vast number of potential variables that previous research has demonstrated to be related to team performance [35] it was only possible to incorporate a small number into the model. Variables were therefore prioritized for inclusion based on theoretical and empirical considerations.

A preliminary theoretical framework for the model was then developed, based on hypothesized relationships between variables identified in the research literature. For example, the hypothesized positive relationship between communication frequency and shared mental model similarity is expected to be influenced, or moderated, by the type of media used (e.g. email, telephone, face-to-face). Furthermore, these relationships in turn are expected to be moderated by the equivocality of the information being relayed.

Based on this framework, we undertook extensive fieldwork, to enable us to populate the model with 'real' data from IPTs operating within two multi-national engineering organizations.

The leaders of 47 engineering teams (ranging in size from 4 to 18 members) were first asked to complete a questionnaire about their team and participate in a 30-minute semi-structured interview. Following this, a second 87-item, psychometrically-sound questionnaire was administered to the members of each team, as defined by their team leader in the initial questionnaire. The brevity of the current paper prevents a discussion of the questionnaire content, however. Traditional statistical analysis techniques, such as multiple regression, were then used to analyze the data and thus inform the rules and equations that would be used within the multi-agent model. This data is now being incorporated into the model gradually, thereby enabling the hypothesized relationships proposed in the preliminary theoretical framework to be explored and validated. The complexity of the model will then be gradually increased, whilst ensuring that the required accuracy is maintained.

It is anticipated that further data collection – using interviews and observation – will be conducted within a smaller number of IPTs to enable us to develop, enrich and calibrate the model further.

SIMULATION

Based on the IPT model described earlier, a multi-agent simulation was implemented using JADE [4], which is an agent-based software framework written entirely in Java language. The simulation will also provide facilities for analyzing the impacts and trade-offs when constructing or revising an IPT performing a specific design task. The simulation is used to host three types of agents, namely a *DesignerAgent*, a *ResourceAgent* and a *TaskManagerAgent*. The states and behaviors for each agent type present within the current version of the simulation are defined in Table 2. It should be noted that the states of each *DesignerAgent* and *ResourceAgent* are actually the key variables, i.e. competency, motivation and availability, within the model. These values are semantically labeled from *very low* to *very high,* and are specified by the users at the start of the simulation.

The simulation's user interface was developed with ease of use in mind.

Figure **4** shows the data entry screens for the individual designers and the design activity's work flow. In addition, the values for all the variables and communication response rate can be modified via a set of pull-down menus. Since a designer with insufficient competency to perform a sub-task will seek information, as shown in Figure 3, a simulation run's result may vary from one instance to another. This is due to the fact that each member within an IPT may have a different response rate. Hence, we include a facility which allows the users to specify the number of simulation runs that they wish to execute. The results of simulation runs can be stored in comma separated variable format, and then used for subsequent analysis. Figure 5 shows typical output results. In order to repeat a simulation run later on, we also provide functions to save and load all the data (i.e. all the variables' values and task's work flow) entered by the users.

Table 2: A summary of the states and behaviors of individual agent types implemented in the simulation.

Agent type	*State*	*Behavior*
DesignerAgent	• Competency • Motivation • Availability	• Perform assigned sub-task • Seek information if its competency is insufficient to complete the sub-task • May response to an information seeking request
ResourceAgent	• Competency • Motivation • Availability	• Always responds to an information seeking request
TaskManagerAgent	• Problem solving demand • Task progress	• Assign tasks to DesignerAgents accordingly • Keep track of task progress

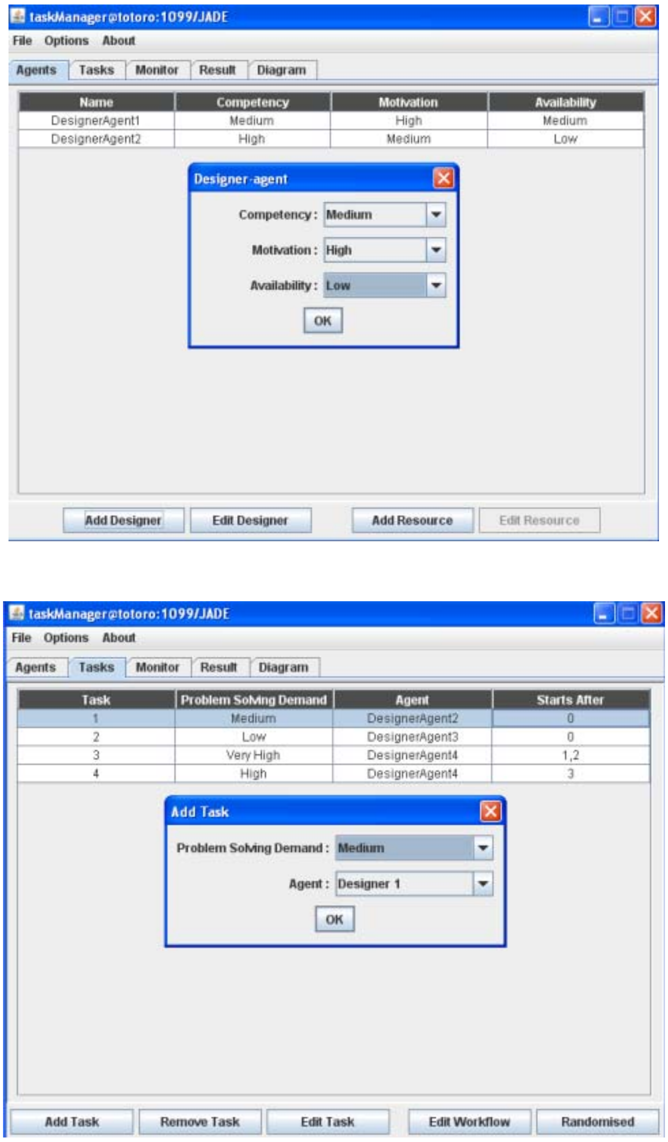
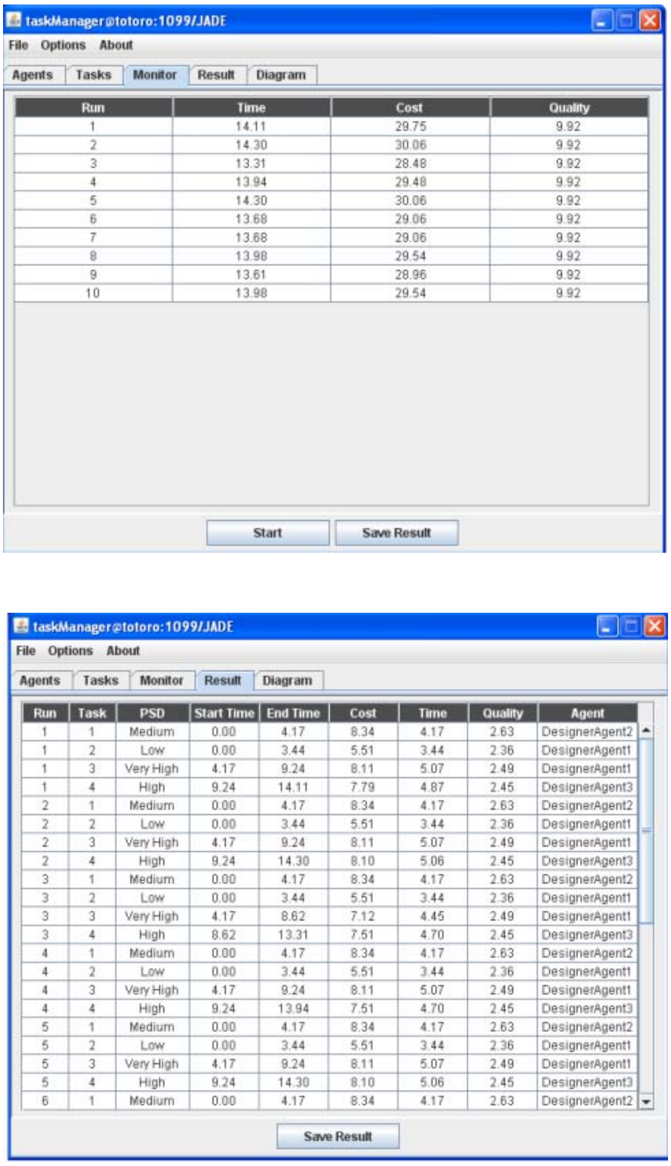


Figure 4: The model's user interface. The upper screenshot shows the variable values for the designers being entered; while the lower screen shot shows the sub-tasks' problem solving demand, allocation and workflow being entered.



Run	Time	Cost	Quality
1	14.11	29.75	9.92
2	14.30	30.06	9.92
3	13.31	28.48	9.92
4	13.94	29.48	9.92
5	14.30	30.06	9.92
6	13.68	29.06	9.92
7	13.68	29.06	9.92
8	13.98	29.54	9.92
9	13.61	28.96	9.92
10	13.98	29.54	9.92

Run	Task	PSD	Start Time	End Time	Cost	Time	Quality	Agent
1	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2
1	2	Low	0.00	3.44	5.51	3.44	2.36	DesignerAgent1
1	3	Very High	4.17	9.24	8.11	5.07	2.49	DesignerAgent1
1	4	High	9.24	14.11	7.79	4.87	2.45	DesignerAgent3
2	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2
2	2	Low	0.00	3.44	5.51	3.44	2.36	DesignerAgent1
2	3	Very High	4.17	9.24	8.11	5.07	2.49	DesignerAgent1
2	4	High	9.24	14.30	8.10	5.06	2.45	DesignerAgent3
3	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2
3	2	Low	0.00	3.44	5.51	3.44	2.36	DesignerAgent1
3	3	Very High	4.17	8.62	7.12	4.45	2.49	DesignerAgent1
3	4	High	8.62	13.31	7.51	4.70	2.45	DesignerAgent3
4	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2
4	2	Low	0.00	3.44	5.51	3.44	2.36	DesignerAgent1
4	3	Very High	4.17	9.24	8.11	5.07	2.49	DesignerAgent1
4	4	High	9.24	13.94	7.51	4.70	2.45	DesignerAgent3
5	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2
5	2	Low	0.00	3.44	5.51	3.44	2.36	DesignerAgent1
5	3	Very High	4.17	9.24	8.11	5.07	2.49	DesignerAgent1
5	4	High	9.24	14.30	8.10	5.06	2.45	DesignerAgent3
6	1	Medium	0.00	4.17	8.34	4.17	2.63	DesignerAgent2

Figure 5: The simulation results are displayed in tabulated format, either for complete runs (upper screenshot) or as a detailed breakdown (lower screen shot). In addition users can choose to save the results data in comma separated variable format for subsequent analysis.

RESULTS

In this section, a typical design activity involving eleven sub-tasks undertaken by an IPT (shown in Figure 6) was employed to generate simulation results for discussion purposes. The design activity was used to investigate the sensitivity to variation in changing the IPT's composition. As the fieldwork for collecting data to develop the IPT model is still actively ongoing, we will only present two case studies that explore the impact and trade-offs of the design output (i.e. time, cost and quality) in relationship to varying the IPT's composition (i.e. by changing the number of designers performing the design sub-tasks and their variable values).

Case Study 1: In the design activity, there are effectively four parallel work paths; hence, only four designers are required to achieve the minimum design time. In this case study the design activity was simulated using one designer at the beginning and additional designers were then added one at a time until we had four of them in the simulation. In addition, the sub-tasks were allocated to designers in a way that minimized the overall design time. Each of the sub-tasks was given a medium problem solving demand value; while all the designers were configured with medium competency and motivation. The designers' availability was set to 70%, meaning that they only spent 70% of their organizational working time on the allocated sub-tasks. The results of the simulation runs are as shown in Table 3. As expected, the overall design time decreases with addition of more designers; while the cost and quality remain constant at 48.66 and 25.70 respectively. This is because by adding more designers, concurrent sub-tasks can be assigned to different people where feasible, permitting the design task to be performed in the shortest time possible.

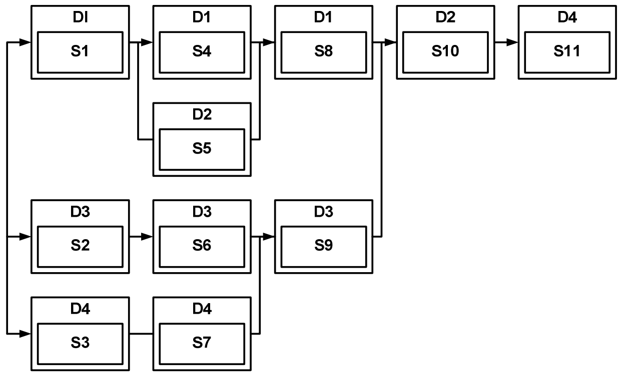


Figure 6: A design activity containing eleven sub-tasks (S1-S11) undertaken by an IPT of four designers (D1-D4).

Table 3: The simulation results for Case Study 1 showing the dependent variables as a function of the number of designers.

Number of designers	*Time*	*Cost*	*Quality*
1	43.45	48.66	25.70
2	27.65	48.66	25.70
3	23.70	48.66	25.70
4	19.75	48.66	25.70

Case Study 2: In practice, an IPT will typically consist of designers with different characteristics (e.g. competency, motivation and availability, as identified in this research work). Using the multi-agent simulation and the design activity illustrated in Figure 6, we can investigate the impact and trade-offs of varying the designers' variable values in an IPT. Four designers were used in this case study, and the sub-tasks' allocation was identical to the one employed in *Case Study 1*. The simulation results for a number of hypothetical IPTs are presented in Table 4. In each IPT, all designers are assigned the same competency and motivation values, while their availability was fixed at 70%. Using *IPT 3* as the baseline, it can be observed that the introduction of designers with higher competency does reduce the time, but increases the cost and quality of the design activity; and vice versa for the cases of *IPT 1* and *2*. Nevertheless, the differences of time in *composition 4* and *5* with reference to *IPT 3* are smaller compared to *IPT 1* and *2*, where designers with lower competency and motivation were employed in the simulation. This is due to the fact that more time was used by the designers in *IPT 1* and *2* to undertake the communication necessary to bring their competency level to medium as required by the sub-tasks' problem solving demand.

Table 4: The results for Case Study 2 showing the dependent variables values as a function of the designers' competency and motivation.

Team	*Competency & Motivation*	*Time*	*Cost*	*Quality*
1	Very low	28.16	43.21	17.85
2	Low	24.25	44.61	21.77
3	Medium	19.75	48.66	25.70
4	High	16.15	49.73	29.63
5	Very high	12.54	50.23	33.55

As noted earlier, the response rate of all designers to an information request varies in accordance with their competency level. Hence the time, cost and quality values in Table 4 are average values obtained from 40 simulation runs

CONCLUDING REMARKS

This paper has described an approach to the modeling of IPTs within large engineering organizations. The model is a heavily modified version of the IDEFØ functional modeling method, additionally including a temporal element, performance metrics, and social aspects. Within the process of developing the model, we have devised relationships between the identified set of key variables that characterize an engineering design environment. It should be recognized that as the fieldwork for data collection is still actively ongoing, some of the assumptions that have been made in the IPT model may need to be refined. Nevertheless, initial feedback from our industrial partners has indicated that the model presented in this paper is a good approximation of the current practice within their IPTs.

Further organizational research involving our industrial partners will be undertaken in order to refine and validate the variables that are currently identified. Additionally, we will be exploring the impact of new variables at a team level, such as shared mental models and trust, in our future work as they may have important roles in influencing the interactions within an IPT. For example, being a team, an IPT consists of two or more members (with a maximum of typically around 20 members) [34], so it is possible that knowledge held by one designer can be supplied to other designers as an external resource or as a control element. The effectiveness with which this knowledge is passed is likely to be influenced by trust and shared mental models. Individual designers bring with them to a team their own perspectives (e.g. terminology and design identities), and these perspectives can be incompatible with those of other team members. Furthermore, for a design team to succeed it is crucial that they pool their resources and perhaps even negotiate a new and different perspective that is accepted by the entire team [15]. Hence, team working requires not only that team members communicate and collaborate with each other, but also that they share a mutual view (i.e. shared mental model) of the design problems. The importance of trust to team performance has also been widely demonstrated (e.g. [5] [1] [30]). Trust can also have a beneficial effect on communication as suggested by Steers and Black [31]. They proposed that communication occurring between people at the same level in the organizational hierarchy can be improved by fostering trust and openness between them.

The innovation within this research lies within the exploitation of the synergy between agent technology and the organizational psychology underlying the interactions within IPTs. Furthermore, our approach also considers both the social and technical aspects of team working, and the interactions between them. The implications are that our work will focus on complex real-world problems, investigated using multiple performance criteria, so that differential impacts and trade-offs can be investigated when constructing or revising IPTs.

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