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MODELLING AND SIMULATING THE EFFECT OF COORDINATION ON PD PERFORMANCE WHILE HANDLING CHANGE

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Abstract

Analysing effect of coordination on performance of complex Product Development (PD) processes and understanding impact of change within PD processes on performance have been recognised as pivotal in acquiring insights into behaviour of PD process. Therefore, this paper focuses on effect of information flow coordination on PD performance while handling change. A computer model was developed to capture PD processes and simulations were carried out considering two communication models, centralised and decentralised. An initiation of change was simulated to study the effectiveness of each communication model while handling change through measuring performance. Results were collated for both with and without change set-ups. Findings showed evidence on existence of a strong relationship between coordinator effectiveness and project performance. Importance of having right number of integrators for coordination with apt communication model was also observed. Moreover, as a result of exploring an under-researched area, the paper also presents suggestions for future research to further develop the understanding of coordinators role in design process in handling changes.

Keywords: Communication, Project management, Simulation, Information management, Knowledge management

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1 INTRODUCTION

Kleinman (1990) has defined coordination as the timely exchange of information and resources, division of and allocation of tasks, and synchronisation of actions. Coates et al. (2004) presented the importance of coordination in achieving expected successful project outcomes through carrying out a review of existing literature. Coordination is necessary across, as well as within organisations—because most organisations are focusing on becoming experts on only a few aspects in a complex product development (PD) process with the view to be more profitable, such that a single organisation or the owners of the process are not capable in executing all the activities necessary to develop the product. Moreover, due to the resource-intensive nature of most of the PD processes, even if an organisation has the capability to complete all PD activities alone, they may often consider gaining additional support from employing individual contractors or sometimes, through using full organisations due to not having adequate levels of resources in-house. This creates a requirement for accommodating suppliers in PD processes. Management of these suppliers forms a key element of the PD process, and is important to achieve successful and competitive outcomes. Hence, organisations utilise principal engineers, project engineers, project managers, etc. (integrators as described in this paper) in supporting as well as monitoring and coordinating suppliers that carry out important design and manufacture tasks. In addition to this coordination workload, integrators tend to have a "day job" within the PD process, which demands their attention to design, project specification and quality assurance work.

In order to analyse complex PD processes and develop insights from an information flow coordination perspective, and to investigate the role of these integrators, the focus of this paper lies on simulating a model representative of a PD process. The objective is to **model the interaction between performance of the PD process and coordination models** and to **analyse the effect of an exogenously instigated engineering change on performance under different coordination mechanisms**. To achieve this, a computer model is developed to capture necessary elements of a generic PD process such as tasks, task dependencies, task durations, and supplier and integrator attributes while accounting for the inherent uncertainty of a PD process.

Then a simulation is employed to compute performance data. Two information coordination models are considered. First, we aim to attain insight into the characteristics of a PD process by studying simulated process performance data under the two different models. Second, the same process model is used to consider the situation in which an instigated design change interferes with the project's progress. The effects of coordination models on the performance of the PD process in both situations are qualitatively compared while highlighting the underlying parameters used in setting up each model. Tentative recommendations for practitioners are drawn and next steps in the research are indicated.

2 AN OVERVIEW OF RELATED LITERATURE

Thompson (1967) observed that the propensity of organisations is to ensure that the technical core is more of a “Closed-system” while keeping the institutional layer (interface of an organisation to the world outside) more of an “Open-system” and utilising the managerial layer as the mediator between them. He also explains that none of the three layers can comprehensively be explained by only one of the strategies, i.e. as either "Closed-system" or "Open-system", but a mixture. This emphasises the importance of coordination and negotiation for the process to function. Suss (2011) highlighted the necessity of efficient coordination mechanisms, for the same reason as above, while developing a computer model to study the inherent uncertainty in complex PD in quantifiable terms and focusing on how an overall PD performance can be improved by appropriate coordination mechanisms. Observations of both authors emphasize the importance of developing further understanding of coordinators or integrators in order to effectively manage large programs having multiple suppliers.

Also considering the role of integrators, Yassine et al. (2003) focus on the impact of information hiding in PD. They focus on the lag between information receipt at an integrator (coordinator) level and release of it after processing the information. They find this is an important contributor to churn in project schedules due to uncertainty and variations inherent to the design work. Furthermore, as Mihm et al. (2003) show, complex product development becomes difficult to manage as projects grow in scope and interconnectedness, even if the associated resource levels are increased proportionately. Eventually, with the increase of complexity beyond a certain threshold, complex product development processes may “diverge” from intended solutions instead of converging towards them. In their model this manifests as the simulated project creating rework faster than it can be resolved. Thus, increasing complexity increases the risk of making the complete venture a failure (Mihm et al. 2003). Mihm et al. (2003) also discuss the increasing need for effective coordination of communication for successful execution of projects as their complexity increases, further supporting Yassine et al.'s (2003) observations. The reader is referred to Jarratt et al. (2011) for a review of further research on engineering change while Malone and Crowston (1994) provide a survey on research on coordination.

3 THE MODEL

3.1 Objectives of the model

This paper presents a simulation of a communication coordination model in PD. This type of model provides a method for evaluating organisational performances which has been used by a number of researchers (e.g. Cohen 1992, Christiansen 1994, Suss 2011). The model in this paper additionally incorporates simulation of change initiation in PD processes, building on prior work of several authors (e.g. Clarkson et al. 2004, Wynn et al 2014).

With reference to section 2 and especially building on Yassine's (2003) and Suss's (2011) research work, this paper extends earlier research to study coordination in complex PD with a special interest in the effect of coordination in the wake of an EC.

The work presented in this paper is preliminary, and makes the following original contributions:

- In existing literature the integrator has been described as a pure coordinator without any responsibility for their own design work. Here work is also allocated to integrators in addition to their coordination work load, in order that the model reflects reality more closely.
- Two communication models are considered in this work, an extension when referred against Yassine's (2003) research. A new resource group “suppliers” is introduced, extending the model in comparison to Suss’ (2011).
- In some scenarios the model is used to simulate instigation of a change that interferes with the ongoing PD process, which helps understand the coordinator effect when dealing with a change.

3.2 Elements of the model

The model has been developed to analyse the relationship between coordination mechanisms and the performance of a PD process, especially under the influence of an exogenously exerted change. The model comprises two different resource types, namely integrators and suppliers, working to complete a set of tasks with interdependencies.

As inputs for simulation, the helicopter dataset reported by Clarkson et al. (2004) and subsequently also used by Maier et al. (2014) was used to define a task network. A set of supplier tasks based on the original helicopter DSM was created assuming a task work load of 175 days for each of the 19 tasks. Since the objective of the present paper is to explore how performance of a PD process might be impacted by different coordination mechanisms, and not to predict performance of a specific process, this dataset is thought to provide a suitable basis for an exploratory study of the issues. Two more inputs were introduced in defining the PD process architecture for simulation, namely an integrator-task map, defining the capabilities of integrators against the task set and similarly, a supplier-task map. These mappings did not form a part of the earlier work (Clarkson et al. 2004, Maier et al. 2014), yet were identified as essential to the work described here in order to differentiate between integrator and supplier workloads and to create a more realistic project model, similar to situations that occur in practice. In the model, every task is mapped to at least one supplier and at least one integrator resource.

Additional numeric inputs required by the model are treated as independent variables in the simulation. Their values were modified to study their impacts in different simulation experiments. These independent variables include: effectiveness of integrators (henceforth described as the integrator factor), time for an agent to process a coordination message received from another agent, maximum time allocated for an agent to work on messages per day (time for messages), whether a change is to be considered during the simulated project (yes or no), location of change initiation (i.e. which subsystem) and the change magnitude as a proportion of the original work required to design the subsystem it impacts. These variables and their meaning in the model are discussed in forthcoming sections.

3.3 Coordination models

Two coordination models are considered in the model, centralised and decentralised. These represent extreme cases at opposite ends of a spectrum of possibilities. Both cases were simulated for identical task networks, with the same resource requirements and resources.

3.3.1 Centralised model

In a centralised model, as depicted in Figure 1 (bottom right), the communication is highly formalised. Integrators are responsible for coordinating all information flow between suppliers, in addition to doing their own work and responding to communication from other integrators. To illustrate, the arrows in the example task network of Figure 1 (top) depict the relationships between tasks and direction of dependencies. Arrows in the corresponding communication model (Figure 1, bottom right) depict the directions of information flows during the simulated process. Each set of lines (Purple, Green, Black and Red) manifests a distinct route through which information may flow. In the model, information flows are represented as discrete messages that are generated by one stakeholder and require response from another. Messages are routed according to the coordination model and queue waiting for attention during simulation. The following hypothetical scenario is provided to clarify the centralised model.

Considering the task DSM and equivalent task network diagram as shown, integrator 1 and supplier 1 are both allocated to task A (main task load of task A and supplier task load of task A respectively) and integrator 2 and supplier 2 are both carrying out work of task B. In the DSM, task B and task A are interdependent. This means that, during the simulated process, supplier 1 may encounter a problem that can only be resolved with input from supplier 2 or vice versa. When this occurs supplier 1 will stop work on task A and raise an information request against task B, manifested as a message. The stronger the dependency in the task DSM, the more frequently this will occur during the simulation. The following points explain the information flow mechanisms of a centralised communication model in this situation.

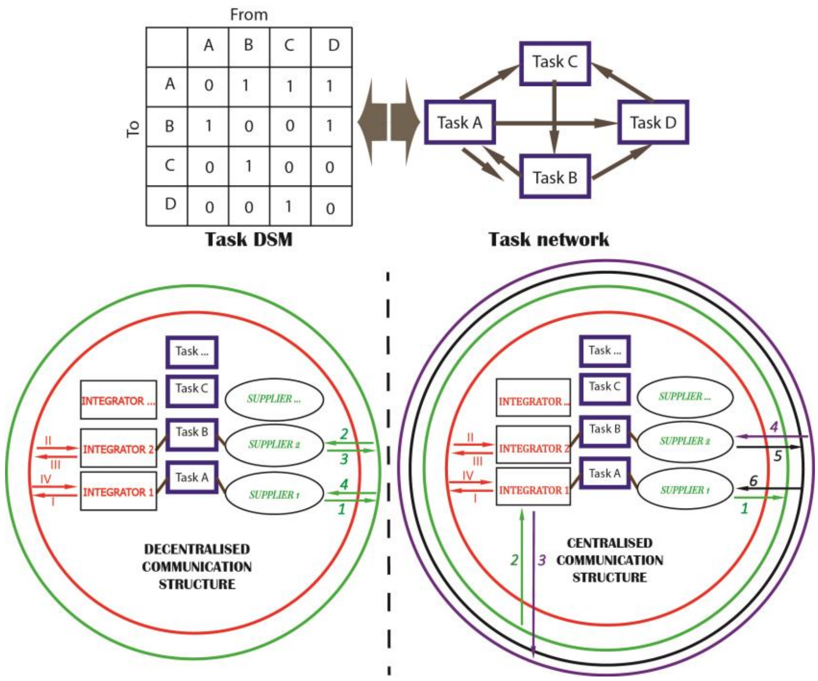

Figure 1. Decentralised (bottom left) and Centralised (bottom right) communication models with related task DSM (top left) and task network (top right)

There are three communication loops in the centralised model for supplier message dissemination and resolution. As shown in Figure 1 (bottom right) each loop represents a different message queue:

- Green queue—Supplier query message loop. Supplier 1 (Sup-1) working on task A encounters a problem requiring coordination to resolve. They stop work on that task and release a message (step 1 in Figure 1, right) to this loop. The message represents a request for information, analysis, etc. that must be dealt with before work can continue. Int-1, who is responsible for coordination relating to task A, later collects that supplier message (step 2) from the loop prior to distribution through purple loop (see next bullet point). There may be a time delay depending on how busy Int-1 is with other messages, and how many other tasks they are responsible for. These delays emerge according to how the process unfolds during the simulation.

- Purple loop—Integrator distribution message queue. The integrator (Int-1) releases the message (step 3) to the queue after stipulating the intended recipient supplier (Sup-2 on task B) during the message distribution cycle. Sup-2 later gathers the message, intending to resolve the query (step 4). Again, there may be a time delay depending on the workload of Sup-2, which emerges dynamically during the simulation.
- Black loop—Supplier reply message loop. Once the query is resolved, Sup-2 releases the reply message (step 5). Sup-1, who was waiting for a response to their original message in order to continue with task A (step 6), will pick up the message and continue their work on task A.

For integrator generated message which requires response from another integrator, there is only one message loop:

- Red loop—Integrator message loop. Integrators Raise, Receive, Reply and Return (I, II, III and IV respectively on Figure 1) messages using this queue. At the point of initiation, messages are given a recipient depending on the task that further information are required from. Replies are directed back to the origin.

In the centralised model, distributing supplier messages increases integrators' workloads, potentially leading to delays in message processing and in the integrators' design work. The advantage is in making use of integrators' insight to ensure that supplier messages are directed to individuals who are able to answer them immediately. This is possible because integrators in principle have a more holistic understanding of the overall project than individual suppliers, often 3rd parties, would.

3.3.2 Decentralised model

Figure 1 (bottom left) depicts an alternative decentralised model in which communication takes place more organically between suppliers. Each supplier has discretion to select the intended recipient supplier who they think is best able to answer each query that arises. In comparison to the centralised coordination model only two loops are applicable: An integrator message queue (Red) and a supplier message queue (Green). The actions of Raise, Receive, Reply and Return for both parties follow similar processes as the integrator loop before, depicted in Figure 1 (bottom left) by the labels 1-2-3-4 respectively for suppliers and I-II-III-IV respectively for integrators.

This communication model reduces integrator workload relative to the centralised model, though it also increases the likelihood of messages being delivered to the wrong recipient because suppliers have a limited understanding of the overall project and its wider teams relative to integrators. The detailed modelling and implications of this are discussed in the next subsections.

3.4 Model logic

3.4.1 Overview of the model

Both models utilise a group of integrators and suppliers performing two separate sets of task loads: a supplier task load set and a main task load set. As evident by the two names, supplier group (called as suppliers from this point onwards) are modelled to be solely responsible for the supplier task set while integrators perform work related to the main task set. This division of responsibility can be observed in real engineering environments. For example, a project an author of the paper was involved in had a similar work breakdown structure where suppliers were assigned specific tasks while integrators (principal engineers in this instance) had their own design workloads on top of the coordination work.

The model acquires the task dependencies, task design times and skill requirements for both task sets from data files. These respectively take the forms of two DSMs, two design data tables and two matrices mapping skill requirements of each task against members of the teams. Figure 2 depicts an example set of input data.

The model operates as follows. At the start of a day:

1. Unblock any integrator tasks that were previously blocked, but can now be continued due to actions on the last loop. First, identify tasks that are blocked because a coordination message was generated earlier by that task. Check all the messages related to the identified tasks. If all the messages related to that task have been answered during the previous loop of the code, release blocked tasks back to the queue of tasks available to execute. Perform the same operation for supplier tasks.

2. Resolve any task deadlocks. As in real project situations, the program considers the overall task progress to identify any stagnation of work by analysing the remaining work elements for both integrator and supplier workloads. If remaining work is observed to have stayed constant over a period of 7 days it is classified here as a deadlock of tasks. In the event of such a deadlock an event representing a full project meeting is activated, thereby ensuring the resolution of any existing messages. It is assumed that such an event consumes a full day of simulation time. During such an event progress of tasks will be reduced to a minimum (0.1 of a day) yet not completely stopped. Similar practices were observed in industry, where major issues hindering progress of projects are resolved by calling up major meetings to clear up outstanding issues, queries, and to make progress on certain aspects of a project as a group.
3. Process integrators. At the beginning of the simulated day, the program starts by selecting an integrator. Then, a full day's worth of time is assumed to be available for the chosen integrator and a task scan is performed while attempting to match the integrator to the required skill sets for the task, as per the detailed skill maps loaded into the model as inputs. Once a suitable match is identified, the integrator starts working on the messages that have been raised against the task and are waiting for attention, spending a certain proportion of the day (as specified in the model input) working on those messages. Then, only for the centralised communication model, attention of the integrator shifts to distribution of supplier messages as per the allocated time for distribution of messages. An elaboration on integrators' treatment of supplier messages is provided in the centralised communication model description.
After handling messages, the integrator moves on to progressing design work for the current task using the remainder of the day. If there are no messages waiting for attention, the whole day will be spent on design work. At the end of the design work, the probability of generating a message related to that work is evaluated by considering the strength of dependencies between the task and all other tasks, the progress so far on these other dependent tasks (on an individual basis) and progress made in the current task by the actor in the active time step. If the evaluation results in a message being generated against another task, the task in hand becomes blocked and a message is recorded in the integrator task message queues. The message includes a reference to the task which generated it and the task which the message is generated against. This loop repeats until the model has studied all the integrators for the current day.
4. Process suppliers. This is comparable to the previous step in many respects and utilises tasks, suppliers and interactions as specified in the appropriate supplier and supplier task matrices. The differences are: absence of a distribution of messages task and having a random condition check before answering a message, representing the integrator effect. Both of these are described further in subsequent sections.
5. Change initiation. Used to study the effect of an exogenous change request halfway through a project, this optional step initiates a change at given time step in one of the tasks as specified in the model inputs by increasing the task load to a level between the initial value and the work remaining for the chosen task.

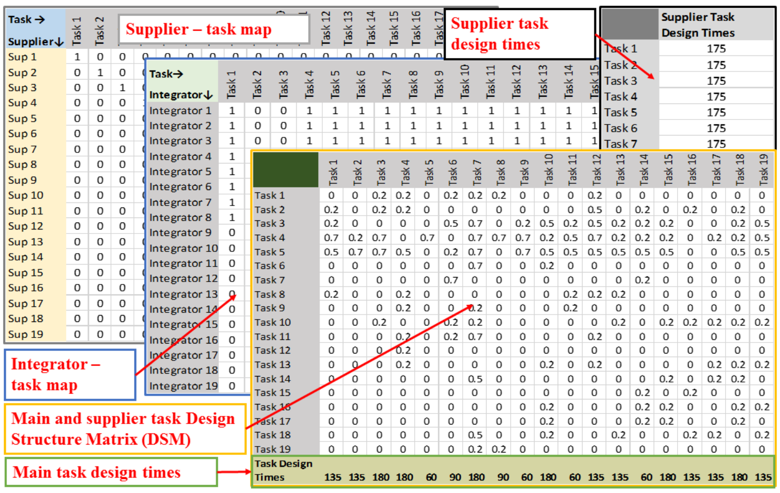

Figure 2. Model inputs (Task DSMs, Task design times, resource maps)

3.4.2 Centralised model

In the centralised model, supplier queries are always transmitted through an integrator. In the model, this increases the chances of the message being correctly answered by the recipient. This property of integrator effectiveness in distributing messages is modelled as the *integrator factor* in the model. We use this to study the influence an integrators' effectiveness has on project performance. The added benefit of choosing the right recipient is represented at the supplier message answering loop through a random check. This random check considers the integrator effectiveness and the strength of the dependency of the sender on recipient. A strong dependency is expected to provide a higher chance of the message being at the right recipient. Integrator effectiveness is also proportional to the probability of a message being answered by the right supplier.

In practice, a recipient, by and large, attempts to answer queries received from colleagues without dismissing them as irrelevant, even if a query appears to be so at the first instance. If a query is found to be unclear (or irrelevant), the normal reaction is to enquire for more information to have it clarified further. Only upon receiving further information and perhaps consulting with the team, one would conclude a message cannot be handled by that team. Thus, sending a message to a recipient who is not equipped to handle it is likely to incur a time delay while they attempt to process it. This situation is modelled using a counter which represents the number of days to be elapsed before a message is realised as irrelevant to the recipient. Currently the counter is set at three, representing a wait of three days. After this, the message passes through to the resolution stage without having to go through the random check again. Three days were chosen as a representative waiting time after considering a general real life situation. For an example if a message to be found unclear by a recipient (day 1), as explained above a reply message enquiring for more information will take place then upon receiving an answer (day 2) to the query another day will at least be elapsed in enquiring from the wider group (day 3) before deciding that the message is irrelevant.

3.4.3 Decentralised model

As described in section 3.2.2, the decentralised model provides discretion to the suppliers in selecting message recipient(s), which as described in section 3.2.2 has limitations as well as advantages. Again, the dependency of a sender task on a recipient task is assumed to be directly proportional to the probability of a query being resolved by the recipient. The logic was developed to represent lack of integrator involvement in distribution of messages by removing the effect of integrator effectiveness factor, hence increasing the probability of the recipient of a message being incorrect. In other words, although each message may reach its destination sooner by skipping the integrator, a greater proportion of messages will be routed to the wrong recipients.

3.4.4 Exertion of an exogenous design change

The arrival of an exogenous design change is represented in the model by an increment in the remaining work load of a given task at a specific point through the project progress. It is expected to cause an increment in project completion time in comparison to project completion time without a change, due to additional work load. Simulations were used to study whether the two different communication models might have different implications in terms of mitigating this impact.

3.5 Summary of model assumptions

Assumptions were necessary in keeping the complexity of the model and the required input data manageable. It is recognised that these assumptions may impact the results gained from simulation, and this issue is discussed later.

Key assumptions in the model are: 1) A supplier message will only be answered by another supplier and not by an integrator-and the same for integrators messages; 2) Supplier work load is uniformly distributed among suppliers at 175 days each; 3) Only a single change request affecting a task will be raised through a given project cycle; 4) Integrator effectiveness will only affect the message resolution probability; 5) Time before a supplier message will be resolved, without any further delays, following a re-enquiry by the recipient supplier is set at three days; 6) A stagnation or a deadlock of tasks is defined as 7 days' of non-variation of task workloads; 7) The Task-Integrator map and Task-Suppliers map were both assumed to allow the exploratory research work described here; and 8) Neither verification at completion of the tasks nor verification at the end of each design phase were considered in this model.

4 SIMULATIONS AND RESULTS

Two base cases were studied for both centralised and decentralised models, one without change and one with change. Two more cases were analysed, of which details are described in subsequent sections.

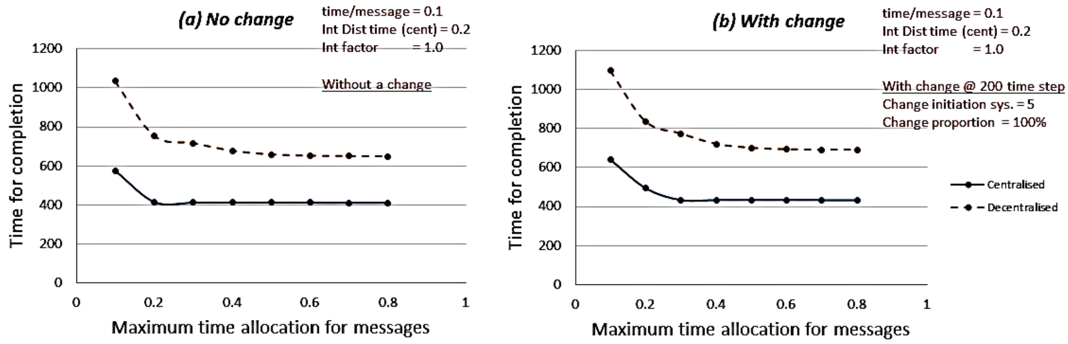

Figure 3. Centralised and Decentralised models, completion time vs maximum time allocation for messages at Integrators and Suppliers. (a) No change (b) With change

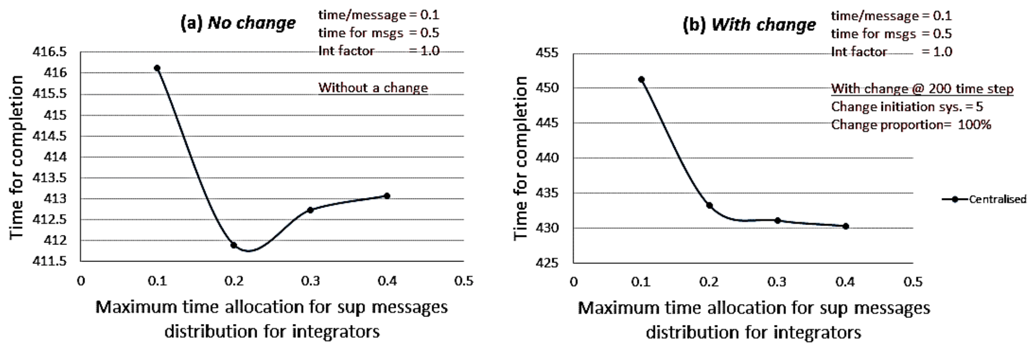

Figure 4 - Centralised model completion time with varying integrator message distribution allocation (a) No change (b) With change

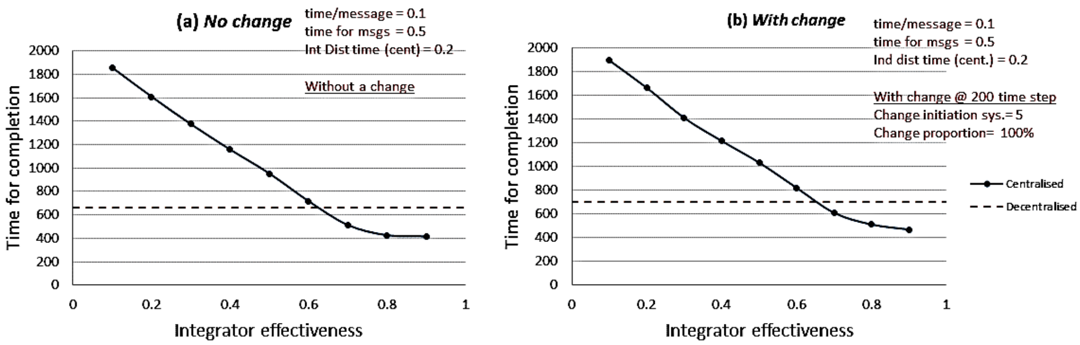

Figure 5 - Centralised model completion time with varying integrator effectiveness (a) No change (b) With change

4.1 Base cases - Centralised and Decentralised communication models

The case without a change assumes an ideal centralised model, with 100% integrator effectiveness, vs. a decentralised model. 1000 simulations were carried out for both situations, varying the maximum allowed integrator and supplier message handling times, from 0.1 to 0.8 at 0.1 intervals on a scale of 0 to 1 (where 1 indicates that the entire day can be spent on processing messages, if there are enough to fill this time). The message distribution time of integrators was left at 0.2 during the simulation. Figure 3 (a) depicts the results. A similar set of experiments was run for the case with change. Task 5 was chosen to instigate a change which required the task to be fully reset on the 200th day of the project. Figure 3 (b) presents the results.

4.2 Centralised case with altering message distribution time allocation

The importance of the maximum time allowed for message distribution each day was then evaluated by recording completion time while altering the allocated message distribution time for integrator resources, as above, integrators was assumed to be 100% effective. Figure 4 presents results, (a) without change (b) with change.

4.3 Integrator effectiveness vs time for completion - centralised model

Integrator effectiveness' impact on completion time was then examined by varying the integrator effectiveness value from 0.1 to 0.9 for two cases, with change and without. Figure 5 shows results.

5 DISCUSSION OF RESULTS

The results reveal that for the simulated case there is a distinct difference in completion time between centralised and decentralised models (Fig 3). Considering the underlying mechanisms allows the following observations to made, which are expected to be applicable to the general case. Qualitatively, centralised time span is lower than the decentralised model if gains made by reduction in the likelihood of messages being directed to the wrong recipient outweigh the penalty associated with increased work load placed on integrators. It was identified that completion time is inversely proportional to the maximum allocated message handling time in the model (combined effect of integrators and suppliers) for both models, up to a point, after which convergence occurs. The reason is that when allocated time for message handling is not adequate, coordination messages tend to queue and design tasks stay blocked for longer until those messages are resolved. As the time allowed for message handling is increased the coordination system starts to become more efficient until a point when the maximum allocated time for handling messages is more than necessary, at which point additional time is available for working on the actual PD tasks. Following this observation, a preliminary recommendation is to prioritise dealing with coordination over other tasks and moreover, to ensure enough integrators are available to prevent coordination bottlenecks from delaying overall progress.

The effect of the time integrators are able to spend on message distribution time (as shown in Fig. 4) was then evaluated. For the case without a change this revealed a bath tub effect indicating that an optimal value exists (Fig 4a). For the case with a change it was observed that although the improvement in completion time that can be gained reduces with further increases in maximum distribution time, there is always still a reduction (Fig 4b). This is mainly due to the increased work load later in the project caused by the change. A preliminary recommendation arising from this observation is that it is important to identify the right balance in time for integrators when dealing with supplier messages, in order to handle changes effectively during a project.

When integrators' effectiveness vs. time for completion was studied, an inversely proportional link became apparent (Fig 5). Furthermore, a trade-off point was observed between the centralised and decentralised models for both with and without change setups (in the specific simulated case the centralised model was more efficient when integrator effectiveness was more than about 70% for both situations). This further underlines the importance of selecting the right coordination model (or increasing the effectiveness of integrators) for each situation.

6 CONCLUDING REMARKS AND FUTURE WORK

The research reported here contributes a model that can be used to simulate a PD process to achieve a qualitative understanding about its performance and the level of effectiveness its integrators should possess. Findings from initial simulations provide support for the existence of a strong relationship between integrator effectiveness and project performance. The results also align with previous research observations that highlight the importance of facilitating adequate levels of communication within a project (Cohen 1992, Christiansen 1994, Suss 2011), as well as research that indicates the effective coordination of communication is a direct contributory factor in ensuring efficient project performance (Kleinman 1990, Coates et al. 2004, Suss 2011).

The results are based on a single case with some hypothesised numerical parameters. As such they should be considered as only preliminary indications of the value of further research into the topic. We recognise the necessity of refining the model further as well as taking steps to validate its mechanisms and outputs. We also anticipate complementing the refined model with empirical insights as this PhD project progresses. The following future work is planned for extending the capabilities of the model: First, provision of guidelines in defining and measuring integrator effectiveness using traits such as skill levels, experience and hierarchical position to concretize the idea of integrator factor within the model is one probable extension, along with the ability to model multiple integrator factors in a simulated project. Second, building rework generation capability into the model due to quality failures, reciprocity etc. as described in existing research (e.g. Christiansen 1994, Suss 2011, Wynn et al. 2014) is also identified as a possible future addition. Third, inclusion of sub-teams and related hierarchical communication patterns (formal and informal) could be beneficial to incorporate more realistic organisational models. Fourth, the ability to reflect the difference between routine and new (complex) workloads, perhaps through measurements of novelty, is desirable. Fifth, incorporating a learning effect as described by Maier et al. (2014) and other researchers should be considered. Sixth, studying multiple changes initiated during a project is identified as an essential inclusion. Finally, the extended version is envisaged to be developed into a tool which can be used by industrial practitioners in identifying better resource levels, team structures, communication pathways, communication intervals and achieving a better budgeting and estimating accuracy, hence improving the PD process performance.

Overall, the contribution of this paper is to take a first look at an important but arguably under-researched area, namely the role of integrators in the design process and in handling design changes, for the case of complex engineering projects involving contributions from multiple suppliers.

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