SIMULATION-BASED MODEL FOR HANDLING ITERATION AND FEEDBACK LOOP IN DESIGN

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ABSTRACT

Iteration is a common phenomenon in design process which improves the design solution and finalizes it for downstream activities as well as for construction. Though iteration is expected, it imposes rework for the design tasks and often delays design completion. In practice, two basic types of iteration can be seen during design. Firstly, activities with sequential dependency can start early if parameter/information produced by the predecessor is estimable. This estimation might not be accurate enough so that reiteration is needed. Secondly, for coupled tasks in complex design process, design can be finalized by "Sit & settle" or through "Repetition" of tasks involved in loop so that design solution converges to a specified workable range. Taking into account the abovementioned issues, probability of rework has been formulated to develop the proposed simulation model. The simulation model has been examined with a few design tasks and found effective quantifying the amount of rework due to iteration and the overall impact on total design duration. Simulation results depict that most of the rework can be scheduled parallel along with other design tasks so that effect of rework is minimal compared to the amount of time can be saved. The results also show that size and position of coupled design tasks have a great impact on design project.

KEY WORDS

Iteration, rework, feedback loop, repetition, sit and settle, simulation model, design completion.

INTRODUCTION

Iteration is a fundamental characteristic of complex design process (Cho and Eppinger 2005) though it is viewed differently by different researchers. As stated in Reinertsen (1997), iteration is a strategy to improve or converge design solution. Similarly, Safoutin and Smith (1996) mentioned that iteration is a technique to solve engineering optimization problem. Moreover, Eisenhardt (1995) conflictingly depicted iteration as a costly problem which should be avoided, a useful means of improving design, or even as a catalyst for innovation. On the other hand, Smith and Eppinger (1997a) describe iteration as the repetition of design tasks due to arrival or discovery of new information which is actually rework of a design task. This rework excludes any repetitive work within a single task's execution (as noticed in Reinertsen) and only

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due to the execution of other tasks (Cho and Eppinger). The current study mainly emphasizes on rework type of iteration which is due to receiving new information while the activity starts its analysis with incomplete information from predecessors and excludes rework due to any external changes to the project or redirection that would involve re-planning the entire process.

In practice, rework due to iteration can be two basic types during the design process. Firstly, if information/parameter(s) produced by a design task can be estimated earlier (i.e. incomplete information), the succeeding activity(s) can be started earlier and hence greater concurrency can be achieved. This estimated information might not be 100% accurate and consequently, reiteration is needed for succeeding activity(s) when it is eventually found to be significantly different (Chua and Hossain 2008). Secondly, iteration is desirable solving coupled tasks in complex design process where no activity can start its analysis with precedent confirmed information. In this case, tasks are allowed to start with incomplete information and design can be finalized by "Sit & settle" or through "Repetition" of coupled tasks so that design solution converges to a specified workable range. However, modeling iteration due to use of early information and handling coupled tasks is still a big concern in design. Design might face unanticipated delay and cost overrun due to surprise rework if not properly quantified and scheduled accordingly. This paper develops a simulation model to quantify the amount of rework due to iteration and feedback loop in design and overall impact on design completion time. The paper also studies the impact of position of coupled tasks that forms a loop and number of tasks involved in a loop.

HANDLING ITERATION IN DESIGN

It is common in design to overlap design activities to shorten project development time. Researchers have described several ways of overlapping such as; Krishnan et al. (1997) modeled overlapping activities with rework iteration by revising downstream activity until upstream information had been finalized. Their model is applicable for a pair of sequential activities but is cumbersome to model the interaction of multiple activities. Oloufa et al. (2004) suggested splitting an activity into sub-activities depending on information requirements by its successors so that some of the successors can start after few days of start of split activity. The study did not consider amount of rework that might be needed if any early released information found significantly different after full completion of split activity. Maheswari and Varghese (2007), on the other hand, modeled design iteration for activities involved in a loop. But, they did not quantify the impact on project duration as a result of rework. Smith and Eppinger (1997a and 1997b) also presented two different iteration models for engineering design. Firstly, they modeled coupled tasks in sequential order where only one task is allowed to start at a time without complete precedent information and rework is also done for its successor based on feedback from that task only. The model only suggests an initial ordering of coupled tasks with minimized expected duration. But this model might yield too much repetition for a task which is not desirable for the project in construction industry. The model also does not suggest how much rework is needed and the overall impact on design completion. In the later model, instead of sequential ordering, they modeled coupled tasks with parallel iteration where a number of design tasks are underway at one time. The model identifies the controlling feature/activity which has dominant effect on couple tasks. However, the model falls short in scheduling the design process with rework and only concerned about the coupled tasks, does not suggest how to incorporate early information to other tasks in the design.

Design project requires both concurrent executions of sequential design tasks through overlapping for which rework might be needed and also handling coupled tasks which are resolved via “Sit and settle” or through “Repetition”. Formulating the probability values of rework for both scenarios is necessary and should be integrated for the whole design process.

MODELING ITERATION AND FEEDBACK LOOP IN DESIGN

Chua and Hossain (2008) showed how using early estimated parameter/information can reduce overall design completion accounting the time required for rework. Instead of traditional finish-start dependency (as depicted in Fig. 1(a)) wherein the succeeding activities start only after the predecessors have completed the full analysis, the study described greater concurrency can be achieved incorporating estimated information in the successors. For instance, if parameter/information from A1 is estimable then A2 can start earlier instead of waiting for the full analysis of A1 as depicted in Fig. 1(b). Similarly, A3 can start earlier if both A1 and A2 are estimable and so on. But the latter is accompanied by the possibility of rework in downstream activities if the values of the parameters deviate from the assumed design range when the parameters are eventually finalized. In general, the parameters utilized in the full analysis are in a combination of states (estimated, full analysis, or confirmed) depending on the status of the predecessor activities. For illustrative purpose, a simple formulation was used setting the probability of rework for an activity in order to quantify total amount of rework that might be needed in a design project.

Earlier study did not consider any coupled tasks in the design project. In practice, design project involves both sequential and coupled tasks as depicted in Table 1 with the design structure matrix (DSM). Here, activity 4, 5, and 6 are coupled tasks forming a loop while rest of activities follows sequential dependency. Rework probability for coupled tasks will be different than the sequential tasks. Formulation to set probability value of rework for sequential tasks will be described first followed by coupled tasks while utilizing early estimated information in design.

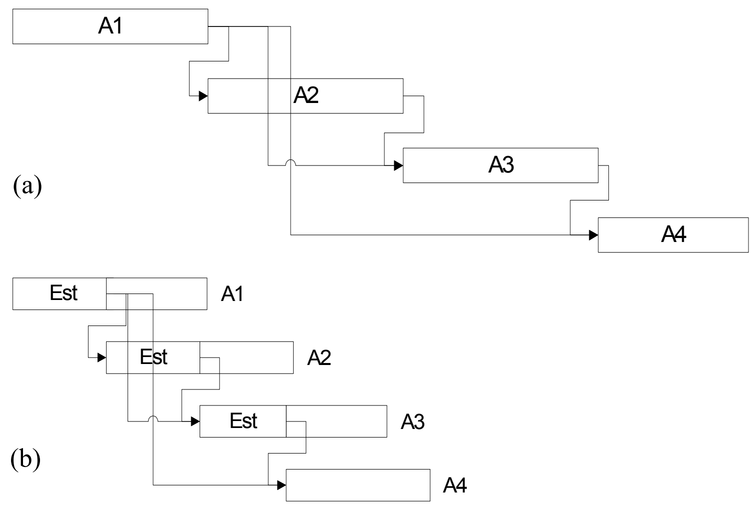

Figure 1: (a) Traditional Finish-Start Dependency, (b) Early Information Sharing with Estimation

Table 1: Activity Dependency with Design Structure Matrix (DSM)

	1	2	3	4	5	6	7	8	9	10
1	x	0	0	0	0	0	0	0	0	0
2	1	x	0	0	0	0	0	0	0	0
3	0	1	x	0	0	0	0	0	0	0
4	0	1	0	x	1	1	0	0	0	0
5	1	0	0	1	x	0	0	0	0	0
6	0	1	0	0	1	x	0	0	0	0
7	0	0	1	0	1	0	x	0	0	0
8	0	1	1	0	1	0	1	x	0	0
9	0	0	0	1	0	1	0	1	x	0
10	0	0	1	1	0	0	0	0	1	x

SEQUENTIAL TASKS

As can be seen in Fig. 1, activity A_4 has two predecessor activities, so that full analysis for A_4 can only be started when it receives parameters from both activities whether it is estimated, from full analysis, or confirmed (as depicted in Fig. 2). If parameter utilized in full analysis of A_4 from A_1 is not confirmed, then there is a possibility that rework might be needed for A_4 when A_1 has been finalized. Assume probability of rework for A_4 due to A_1 is $P_{1\text{-}4}$. Similarly, probability of rework for A_4 due to A_3 is $P_{3\text{-}4}$. Activity A_4 may receive confirmed parameter from its predecessors at different times. If A_4 is allowed to do iteration every time it receive updated parameter from predecessors, then it will need a number of iterations and if A_4 has any successor then it will transmit revised parameter to its successor causing several iterations to the successor activities as well. This will result in large amount of rework for the design process which is costly and time consuming and make it difficult to handle information interaction within multi-discipline activities. Lean thinking also suggests reducing unnecessary/negative iteration in design. Consequently, in this study, A_4 is allowed to iterate only when it gets confirmed information from all its predecessors. Assuming rework probability due to A_1 and A_3 is independent, combined probability of rework for A_4 can be determined as:

$$P_4^c = 1 - (1 - P_{1-4}) * (1 - P_{3-4})$$

In general,

$$P_y^c = 1 - \prod_x (1 - P_{x-y}) \quad (1)$$

where, x is the predecessor for A_y

As stated earlier, the parameters utilized in the full analysis are in a combination of states (estimated, full analysis, or confirmed). When full analysis of an activity is initiated, it will draw the most updated parameters from its predecessors and probability of rework, P_{x-y} for individual activity depends on the type of parameter used in the full analysis.

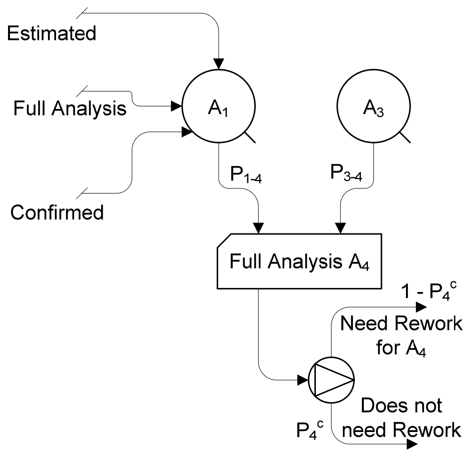

Figure 2: Probability Value of Rework in Simulation Model for Sequential Dependency

If the extracted parameter is

Estimated, $P_{x-y} = (1 - DA_x) * IF_{x-y}$ (2a)

Full analysis, $P_{x-y} = P_x^c * IF_{x-y}$ (2b)

Confirmed, $P_{x-y} = 0$ (2c)

Here, DA_x refers to "Degree of Accuracy" for the estimated parameter of predecessor activity A_x. This is a measure of probability value that estimated parameter will remain within an acceptable range in the latter states. The higher value of degree of accuracy refers to lower probability of rework for the successor and vice versa. And, IF_{x-y} stands for "Influence Factor" for activity A_x to activity A_y. This notation describes the strength of influence that any change in A_x will cause rework to activity A_y. Both values (DA and IF) can be assigned by the designer depending n the characteristics of activity and past experience. As depicted in Smith and Eppinger (97a), probability value of each cell can be represented as the strength of influence so that corresponding row activity might need revision due to any change in corresponding column activity. Knowing the probability that earlier parameter will change and the influence factor, combined probability of rework can be found due to a specific predecessor.

COUPLED TASKS

In the case of sequential activities, check for rework is done only once when all confirmed parameters from predecessors are available. For coupled tasks, confirmed parameters are dependent on each other and it is not likely that confirmed parameters can be obtained with single iteration. It might need several iterations before the design solution converges to a specified workable range. Probability of rework for coupled tasks can be modeled as depicted in Fig. 3 where activities 4, 5, and 6 form a loop and shown with dotted lines.

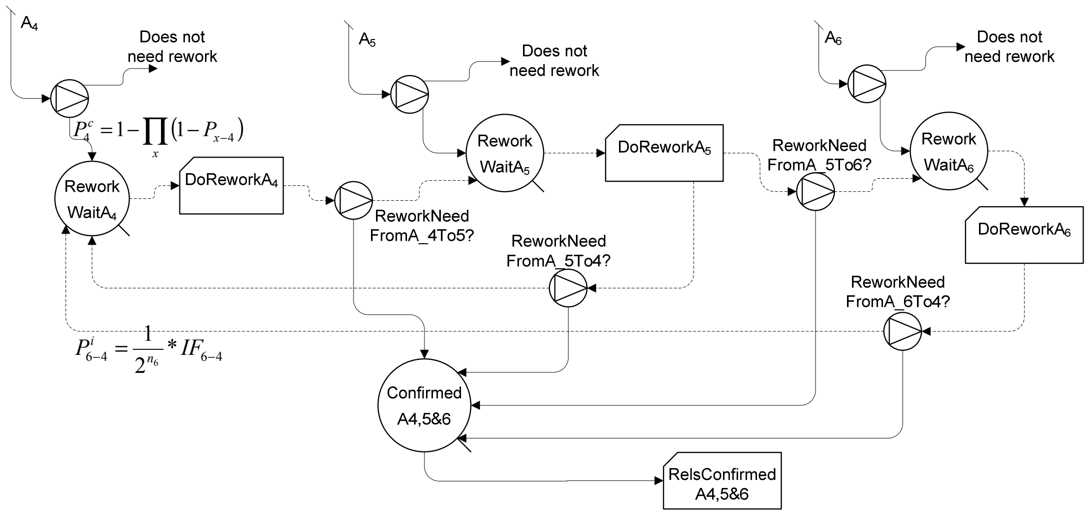

Figure 3: Probability Value of Rework for Coupled Tasks if Solved by "Repetition"

After performing the full analysis of coupled tasks and receiving confirmed After performing the full analysis of coupled tasks and receiving confirmed parameters from all predecessors except those involved in the loop, check for first iteration will be done. Subsequent checks will be needed if any of the predecessor coupled task has been reworked. This check will be done every time any of the predecessor coupled task is reworked and the rework probability is,

$$P_{x-y}^i = \frac{1}{2^{n_x}} * IF_{x-y} \quad (3)$$

where, n_x is the number of iteration has been done for coupled activity A_x.

The equation depicts an exponential decay function for probability which decreases quickly for first couple of iterations since design solution converges very fast at this stage. After few numbers of iterations, design solution will fall within a specified workable range and no task will need further iteration and coupled tasks will transmit confirmed parameters to their successor.

The abovementioned iteration of coupled design tasks may not be desirable in some design project, especially when iterations are costly. In such case, design is finalized by "Sit and Settle" among the coupled tasks which can be modeled as shown in Fig. 4. Instead of doing several iterations, all the designers of the coupled tasks sit together for some time after finishing full analysis and find whether any of them need to revise their analysis. If revision is needed for any task, they are given some time to finalize their parameters. This check might be required in more than one time but with lower probability value. Rework probability for "Sit and settle" is:

$$P^s = 1 - \prod_x \left(1 - P_x^c\right) \quad (4)$$

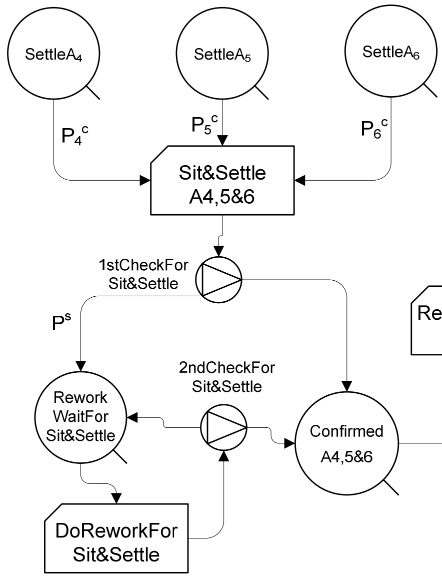

Figure 4: Probability Value of Rework for Coupled Tasks if Solved by "Sit and Settle"

RESULT AND ANALYSIS

With abovementioned formulation for probability of rework, a simulation model has been developed using STROBOSCOPE (Martinez 1996). Initially, the effectiveness of the proposed model has been examined with a case study from Smith and Eppinger (97a) as in Fig. 5(a). The Figure shows a part of the electric car design project depicting a single loop of 8 activities. Dependencies between activities are shown in the matrix with the durations for activities in diagonal elements of the DSM. According to Smith and Eppinger, design requires about 30 days. Incorporating early information and accounting for rework, design completion can be significantly reduced to about 18 days. There is little difference in the completion time whether the loop is solved doing "Repetition" or by "Sit and settle". If the estimated parameters are accurate enough so that rework is unnecessary, full analysis for the loop can be finished by day 15. Though an additional 7 mandays of rework is needed to settle down design solution, overall completion time is much lower than the earlier study. These 7 days of lost of productivity is not directly translated into delaying design completion time since most of the rework can be scheduled parallel along with other design tasks.

Position of coupled tasks (that form a loop), number of tasks involved in a loop, and how the loop is solved ("Repetition" or "Sit and settle"), can affect design completion time. These effects can be depicted in Table 2 which shows the results for four different scenarios depicted in Fig. 5(b). The same ten activities of Table 1 have been examined for the four scenarios. In scenarios (1) and (2), three activities are involved in a loop while in scenarios (3) and (4); the loop is bigger consisting of five activities. In scenarios 1 and 3, the loop occurs in the middle of the design process while in scenarios 2 and 4, it occurs near to the end. If no activity is estimable then everyone has to wait for the completion of full analysis of the predecessor and the design project requires 160 days. Incorporating early estimation, for all four cases, design can be completed on day 76 (52% reduction) if estimated parameters are assumed to be accurate. Since estimated parameter may not be accurate, it is assumed that estimation is 50% accurate; i.e. there is a probability of 0.5 that estimated value will change when parameters are finalized. Estimation time is taken as 40% of the original full analysis for an activity. Also, Influence Factor is taken as 0.8 to reflect a probability of 0.8 that any change in parameter value will cause rework to its successor. The impact has been observed for two different fraction of time to do rework for each activity.

		1	2	3	4	5	6	7	8
Total weight	1	1	0	1	1	0	1	1	1
Speed and acceleration versus power	2	1	2	0	0	0	0	1	1
Speed and acceleration conformance	3	0	1	1	0	0	0	0	0
Motor specifications and weight	4	1	0	1	2	0	1	1	0
Stored energy requirement	5	0	1	0	1	1	0	0	0
Battery size and weight	6	0	0	0	0	1	1	0	0
Size and aerodynamics	7	0	0	1	1	0	1	7	1
Structural and suspension design	8	1	0	1	1	0	1	1	5

(a) Smith and Eppinger 97a

	1	2	3	4	5	6	7	8	9	10
1	20	0	0	0	0	0	0	0	0	0
2	1	20	0	0	0	0	0	0	0	0
3	0	1	20	0	0	0	0	0	0	0
4	0	1	0	20	1	1	0	0	0	0
5	1	0	0	1	20	0	0	0	0	0
6	0	1	0	0	1	20	0	0	0	0
7	0	0	1	0	1	0	20	0	0	0
8	0	1	1	0	1	0	1	20	0	0
9	0	0	0	1	0	1	0	1	20	0
10	0	0	1	1	0	0	0	0	1	20

Example (1)

	1	2	3	4	5	6	7	8	9	10
1	20	0	0	0	0	0	0	0	0	0
2	1	20	0	0	0	0	0	0	0	0
3	0	1	20	0	0	0	0	0	0	0
4	0	1	0	20	0	0	0	0	0	0
5	1	0	0	1	20	0	0	0	0	0
6	0	1	0	0	1	20	0	0	0	0
7	0	0	1	0	1	0	20	1	1	0
8	0	1	1	0	1	0	1	20	0	0
9	0	0	0	1	0	1	0	1	20	0
10	0	0	1	1	0	0	0	0	1	20

Example (2)

	1	2	3	4	5	6	7	8	9	10
1	20	0	0	0	0	0	0	0	0	0
2	1	20	1	0	0	1	0	0	0	0
3	0	1	20	1	1	0	0	0	0	0
4	0	1	0	20	1	1	0	0	0	0
5	1	0	0	1	20	0	0	0	0	0
6	0	1	0	0	1	20	0	0	0	0
7	0	0	1	0	1	0	20	0	0	0
8	0	1	1	0	1	0	1	20	0	0
9	0	0	0	1	0	1	0	1	20	0
10	0	0	1	1	0	0	0	0	1	20

Example (3)

	1	2	3	4	5	6	7	8	9	10
1	20	0	0	0	0	0	0	0	0	0
2	1	20	0	0	0	0	0	0	0	0
3	0	1	20	0	0	0	0	0	0	0
4	0	1	0	20	0	0	0	0	0	0
5	1	0	0	1	20	1	0	0	1	0
6	0	1	0	0	1	20	1	1	0	0
7	0	0	1	0	1	0	20	1	1	0
8	0	1	1	0	1	0	1	20	0	0
9	0	0	0	1	0	1	0	1	20	0
10	0	0	1	1	0	0	0	0	1	20

Example (4)

(b)

Figure 5: DSM for Different Design Projects

Accounting for rework and with larger time to do the rework, design requires longer duration if the loop is solved by "Repetition" compared to "Sit and settle" for all four cases. This is because, in "Repetition", each task in the loop may require a numbers of revisions due to receiving new information from its predecessors. In the case of "Sit and settle", tasks are not revised several times so that design is finalized quicker. However, with shorter time to do rework, design duration is almost the same for "Repetition" and "Sit and settle" for the scenarios (1) and (2), with the smaller loop. Where as with larger loop, design requires much longer time for "Repetition" compared to "Sit and settle". Since each rework duration is short; the design can be settle fast in a few iterations. However, it takes more iteration to settle the design for a larger loop

Table 2: Simulation Results for Different Scenarios

Scena-rio	**No. of activ i-ties in loop**	**Positi -on of loop**	**Loop solved by**	**Time to do rework is 50% of the original full analysis**			**Time to do rework is 20% of the original full analysis**		
				Total duration	**% Lost of productivity in mandays**		**Total duratio n**	**% Lost of productivity in mandays**	
					For activitie s in Loop	**For others activitie s**		**For activitie s in Loop**	**For others activitie s**
1	3	Middl e	Repetitio n	104.7	45.2	25.5	80.1	16.5	10.1
			Sitting	100.6	32.2	25.0	79.8	15.0	10.6
2	3	Near to the end	Repetitio n	98.0	55.3	16.9	84.7	21.3	6.9
			Sitting	93.7	34.3	17.7	84.4	16.8	7.0
3	5	Middl e	Repetitio n	121.9	73.8	31.4	85.5	29.7	12.7
			Sitting	105.7	34.8	31.7	81.4	18.1	12.7
4	5	Near to the end	Repetitio n	112.7	87.9	15.6	90.3	33.2	6.3
			Sitting	94.1	35.0	16.1	84.7	17.8	6.4

The impact of number of tasks in a loop is evident from Fig. 6 which shows the number of iterations needed for activity A_8 to finalize the design for 1000 simulation runs. As can be seen, for the small loop, A_8 does not need any rework about 20% of time and in a single iteration, it can be solved more than 50% of time. On the other hand, with the larger loop, A_8 needs higher numbers of iterations: it can be solved by a single iteration in only 36% of time; 38% of time it need two iterations; 10% of time it requires three iterations and even sometimes it requires fourth iterations. So, larger loop will cause greater delay in transmitting confirmed parameter if loop is solved by "Repetition".

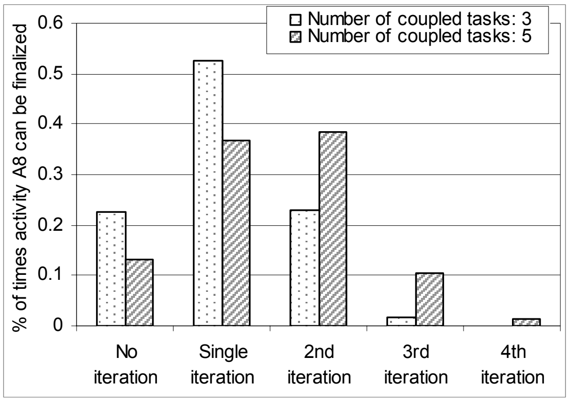

Figure 6: Number of Iterations Needed for Activity A_8 to Finalize the Design

The position of loop in design has also great impact on design completion time. If loop is placed earlier in design and time to do rework is low then most of the rework can be scheduled parallel along with other design tasks so that overall impact on design duration is minimal, as can be compared between examples (1) and (2), and also between (3) and (4) in Table 2.

Table 3 depicts the impact on design completion and lost of productivity for different "IF with time to do rework taken as 20% of the original full analysis. If influence factor is low, then design completion is earlier for "Repetition" compared to "Sit and Settle", irrespective of size and position of loop. This is because, with lower "IF", probability of rework is low and the design loop can settle faster. However, "Sit and Settle" requires some time for arranging meeting date to resolve the loop. With higher "IF", design completion is earlier for "Sit and Settle" than "Repetition", especially, if loop is larger.

Table 3: Impact of Influence Factor "IF" between Activities

Scena-rio	Loop solved by	Low IF (0.2)			Moderate IF (0.5)			High IF (0.8)		
		Total durat-ion	% Lost of productivity in mandays		Total durat-ion	% Lost of productivity in mandays		Total durat-ion	% Lost of productivity in mandays	
			For activi-ties in Loop	For others activi-ties		For activit-ies in Loop	For others activit-ies		For activit-ies in Loop	For others activi t-ies
1	Repetition	76.8	2.7	3.0	77.9	8.8	6.6	80.1	16.5	10.1
	Sitting	77.0	6.3	3.1	78.3	12.7	6.8	79.8	15.0	10.6
2	Repetition	78.1	4.3	1.8	81.3	11.8	4.4	84.7	21.3	6.9
	Sitting	79.6	6.5	1.6	82.5	13.7	4.4	84.4	16.8	7.0
3	Repetition	78.0	5.0	4.3	80.4	16.3	9.2	85.5	29.7	12.7
	Sitting	78.2	12.1	4.3	79.4	16.9	9.2	81.4	18.1	12.7
4	Repetition	80.2	5.9	1.6	85.9	18.4	3.9	90.3	33.2	6.3
	Sitting	81.7	12.3	1.6	83.8	17.0	4.0	84.7	17.8	6.4

CONCLUSION

This paper proposes a simulation model setting probability value of rework for sequential and coupled tasks in design while utilizing early estimated information. The simulation model can dynamically set this probability value while design progresses. The model is found to be effective quantifying loss of productivity due to iteration and overall impact on design duration. Simulation results reveal that effect of rework is minimal compared to the amount of time can be saved for design completion, since most of the rework can be scheduled parallel along with other design tasks. The results also depict that if coupled tasks are solved by "Repetition", design requires higher time compared to "Sit and settle" if the loop contains more activities or time to do rework is high. With small loop and shorter time to do rework, there is no difference in design completion if loop is solved by "Repetition" or "Sit and settle". Though "Sit and Settle" is better way to solve a loop in design, it is not always possible to go for it, especially if couple tasks are geographically dispersed.

As can be seen form the analysis, position of coupled tasks also has a great impact in design. Coupled tasks at the end of design delay the transmission of confirmed parameter and hence overall design completion. Where as, if coupled tasks are at early stage of design, then delay of transmitting confirmed information can be accommodated with other design tasks, especially if time to do rework is low. Moreover, simulation results depicts that "Repetition" is better when Influence Factor is less and with higher "IF", "Sit and Settle" technique become better, especially if loop is larger in size.

This paper provides effective way of handling rework in sequential design tasks as well as solving coupled tasks. Based on the characteristics of design project, decision makers will be able to quantify the design completion taking into account the time required for rework and can decide which method they should adopt to solve their design. Though loss of productivity causes extra cost to the project, it can be outweighed by the time that can be saved using early estimated information in design. Cost analysis could be further extension for the current research.

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