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Evaluating the Effectiveness of Task Overlapping as a Risk Response Strategy in Engineering Projects

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Abstract. In the last two decades, the failure of multiple engineering projects has highlighted the importance of adopting risk management practices. While risk identification and risk assessment have been widely studied in the literature, only few authors have proposed formal tools for helping project managers to evaluate the effectiveness of their risk response plan. While some risk response measures might be easily validated, overlapping, a commonly used mitigation measure in engineering projects is difficult to evaluate because of the complex interactions between activities and resources. This paper proposes an evaluation model to measure the effectiveness of overlapping strategy as a risk response in terms of additional cost and total maximum time reduction. Results based on a large set of generated projects highlight the importance of three factors in the effectiveness of an overlapping strategy: the number of opportunities of overlapping, the maximum overlapping amount allowed, and the level of resource constraints.

Keywords. Project management, risk management, concurrent engineering, activity overlapping, scheduling.

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1 Introduction

Most project schedules are developed in a deterministic manner where activity durations correspond to a single value, usually the most likely duration. The assumption is that the duration is known with some certainty. However, the schedule often contains significant uncertainty, especially in complex technical environment and in new product development projects. In fact, these types of projects are usually composed of a large number of interrelated tasks. The complexity of the information flow as well as the possible dependency between tasks make the project scheduling difficult and unsteady. The potential need of repeating a certain task within the development process also worsens the situation (Chen *et al.* 2003).

In the last two decades, the failure of multiple engineering projects has highlighted the importance of adopting risk management practices (Lee *et al.* 2009; Williams, 1995). Project risk management aims at reducing risk by developing a project plan which minimizes the uncertainty and by implementing strategies which maximize the probability of achieving the project goals. Various studies have discussed means of conducting risk management by proposing formal processes for achieving project success (Cooper *et al.* 2005; Patterson and Neaily, 2002; Smith and Merrit, 2002; Chapman, 1997). While the proposed process and the terminology may differ from one author to another, the general risk management process consists of four main phases: risk identification, risk assessment, risk response planning, and risk control.

Among these phases, risk identification and risk assessment have been the most widely studied in the literature. For instance, several risk analysis tools or frameworks were proposed to identify and quantify the risks in new product development projects (Choi and Ahn 2010; Kavis *et al.* 2006). Most traditional risk assessment approaches result in probabilistic analysis.

On the other hand, only few authors have proposed formal tools for helping project managers to evaluate the effectiveness of their risk response plan, also called the risk mitigation plan. This plan, which may include various risk avoidance, risk reduction, and risk transfer measures, is however crucial in complex projects by formalizing the risk contingency strategy of the organization.

While some risk response measures might be easily validated, others might be more difficult to evaluate in engineering projects. Engineering projects involve many variables and it is often difficult to determine dependence and correlations between them. For instance, overlapping is a core technique for reducing development time (Bogus *et al.*, 2005; Terwiesch *et al.*, 1999; Smith *et al.*, 1995; Smith and Reinertsen 1998) and is widely used as a risk response strategy when anticipating development delay in the early phases of projects. Overlapping consists in starting an activity before receiving all the final information required. Its efficiency for reducing product development time has been proved in the aerospace (Sabbagh 1996) and automobile industries (Clark and Fujimoto 1991). However, this practice often causes future rework and modification as new information is gained in subsequent activities. In some cases, rework may outweigh the benefits of executing activities in parallel (Terwiesch *et al.*, 1999). The real benefits of activity overlapping also largely depend on the nature of the project schedule as overlapping creates interactions between activities. As such, the project topology, as defined by its network and the resource constraints may greatly affect the effectiveness of overlapping measure. Consequently, the total expected reduction of time is difficult to evaluate and additional costs associated with rework are often ignored in the project planning phases. It is therefore not surprising to note that most companies determine overlapping strategies on an ad hoc basis without always considering rework (Lin *et al.*, 2009). Most contributions in the literature also failed to consider the impact on resources when planning overlapping development activities or are limited to measuring the project time reduction obtained through overlapping a posteriori by analyzing completed projects (Terwiesch and Loch, 1999).

In this paper, we propose a different approach by presenting a predictive model taking into account the interactions between activities and resource constraints. Our objective is to propose a contingency plan evaluation model to measure the effectiveness of overlapping strategy in terms of additional cost and total maximum time reduction. This paper is based on a deterministic resource scheduling model which determines the optimal sets of overlappable activities and modes. The calculated project makespan improvement can then used as an upper bound which defines the maximum gain that can be obtained by accelerating development activities through overlapping. These results allow project managers to determine if overlapping is an adequate risk reduction measure and what are the additional budget requirements associated with that strategy if implemented during the project execution.

The remainder of the paper is organized as follows. Section 2 first presents a brief review of overlapping execution studies. Section 3 describes the proposed solution approach followed by the description of the experimental data set used in this study in Section 4. Computational results are then presented in section 5. The paper concludes with recommendations for future work in section 6.

2 Literature review

Overlapping depends not only on dependency between activities but also on information exchange policy between upstream and downstream activities and progress evolution. Two groups of models have been developed in the literature to analyze overlapping interactions. First, many authors consider only couples of activities and no resource constraint to establish the best trade-off between overlapping and rework. For instance, Krishnan *et al.* (1997) developed a model-based framework to manage the overlapping of coupled activities. This model introduces the concept of information evolution and downstream sensitivity to describe interaction between both activities. Information evolution refers to the upstream generated information useful for downstream activities. Downstream sensitivity refers to the impact of a change in upstream activity on the downstream activity. The more significant the impact is, the higher the sensitivity is.

Relying on these concepts, Krishnan (Krishnan, 1996) defined different types of appropriated overlapping strategies: iterative, preemptive, distributive and divisive overlapping. In a similar manner, Bogus *et al.* (2006) identified appropriate strategies to efficiently implement overlapping in practice. Lin *et al.* (2009) also improved the overlapping model by incorporating the downstream progress evolution and determined the optimal overlap amount. These models assume that overlapping parameters can be derived from historical data of projects.

Other approaches have considered whole projects instead of couples of activities under the assumption that relation between overlap amount and rework is preliminary known for overlappable activities. They mostly use design structure matrix (DSM) to represent dependencies, to minimize feedbacks, and to identify overlapping opportunities between activities. DSMs were introduced by Steward (1981). Among these models, Gerk and Qassim (2008) developed an analytic project acceleration linear model via activity crashing, overlapping and substitution with resource constraints. Wang and Lin (2009) developed a stochastic overlapping process model to assess schedule risks. Their simulation model considers iterations and probabilities of rework. Iterations are mostly defined as interaction between design activities which lead to rework caused by feedbacks from downstream activities.

However, these models do not take into account resource constraints, except for Cho and Eppinger (2005) who introduced a simulation model with stochastic activity durations, overlapping, iterations, rework, and resource constraints for some activities. They showed that these constraints can delay some overlapped activities and delay the project. All these models assume a simple linear relationship between rework and overlap amount with an upper bound and a lower bound.

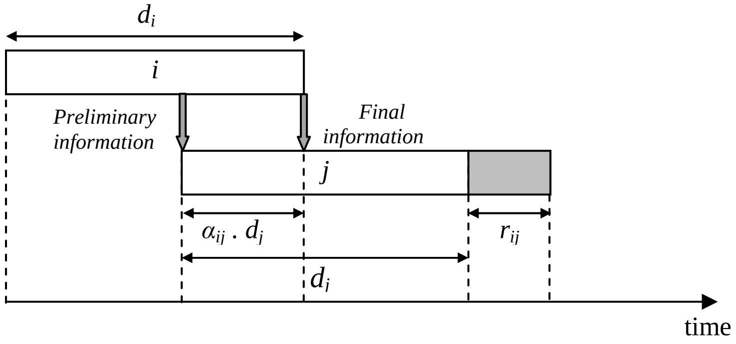
3 The proposed approach

A project is defined by a set of *n* activities, including two fictitious activities *0* and *n+1*, which correspond to the project start and project end, with zero processing time. We denote by d_j the nominal processing time of activity *j* considering that all the final information required from preceding activities are available at its start; in other words, if activity *j* is processed without overlapping.

It is here assumed that a project is only composed of independent and dependent activities. The resulting information flow within the project between activities is assumed to be unidirectional from upstream to downstream activities. The analysis of information exchanges between dependent coupled activities enables to categorize them into non- overlappable and overlappable ones. The former represents the case where a downstream activity requires the final output information from an upstream activity to be executed or the completion of the upstream activity. The latter represents the case where a downstream activity can begin with preliminary information and receives final update at the end of the upstream activity. This relation provides the opportunity to overlap two activities so that a downstream activity can start before an upstream activity is finished. While the non-overlappable activities are connected with the classical finish-to-start precedence constraint, the overlappable ones are connected with a finish-to-start-plus-lead-time precedence constraint where the lead-time accounts for the amount of overlap (Cho and Eppinger, 2005).

Figure 1 shows the overlapping process of an overlappable couple of activities *i* and *j*. The downstream activity *j* starts with preliminary inputs from the upstream activity *i*. The amount of overlap, α_{ij}, is expressed as a fraction of the downstream activity duration. An additional rework is often necessary to accommodate the changes in the upstream information in the downstream development. The expected duration of this rework is denoted by r_{ij}.

Figure 1: Overlapping process of two activities



An important part of the literature on overlapping process is dedicated to the determination of the optimal overlap amount for a couple of activities without resource constraint (Krishnan et *al.*, 1997; Roemer et *al.*, 2000; Terwiesch and Loch, 1999). However, the optimal overlap amounts for a resource-constrained project composed of several couples of overlappable activities are not necessarily set to the optimal values found for each couple of activities (Cho and Eppinger, 2005; Gerk and Qassim, 2008; Browning and Eppinger, 2002).

To determine the optimal schedule when overlapping is allowed, we propose a linear 0-1 integer programming model which is based on a previous model developed by Berthaut *et al.* (2011). Within this resource constraint scheduling model, presented in annex, overlapping is supposed to be performed for discrete values of overlap amount. In practice, however, scheduling is performed on a period by period basis and activity progress is measured according to the completion of milestones, corresponding to activity deliverables. Therefore, we consider a finite number of different overlap amounts aligned with activity milestones. These different values constitute the different feasible modes. Each mode is characterized by a specific amount of overlap and associated rework duration.

In order to represent the impact of overlapping on the execution cost, the overlapping costs is assumed to be composed of the cost of rework and the additional coordination cost. The coordination cost is considered negligible, which is also the case in previous works (Gerk and Qassim, 2008; Krishnan *et al.*, 1997). It is assumed that rework cost is considered as a linear function of the time spent on rework, where the linear factor is the average wages of the teams per unit of time. It is also assumed that all resources have the same period rate (*i.e.* the resource use cost is estimated at $100 per period for all resources).

Experimental results are presented in the next section.

4 Experimental data

In order to demonstrate the importance of project characteristics, and the necessity to consider resource constraints when evaluating the maximum time reduction that can be obtained by adopting overlapping measures, we tested the proposed approach with different projects having similar characteristics.

A reference project consisting of 30 activities was used to build our expiremtal data set. The PROGEN project generator (Kolish *et al.*, 1992) was used to generate comparable project networks and resource demand. All projects involved 4 renewable resources. As in Kolisch *et al.* (1992), we use three main parameters to define our project data set: the project complexity *C*, the resource factor *RF*, and the resource strength factor *RS*. The complexity parameter is defined as the average number of arcs per node. This parameter describes the complexity in relations and dependences between activities and is used to construct the activity-on-node project networks. The resource factor is calculated as the average portion of requested resources per activity. If *RF=1*, all *4* resources will be needed for each activity. Instead, if *RF=0.5*, then each activity will require in average *2* different types of resources. The quantity of each requested resource is randomly calculated between the minimum and maximum allowed values. Finally, the resource strength factor characterizes the relation between resource demand and resource availability. Kolish *et al.* (1992) present a methodology to determine resource availability with this *RS* factor:

$$Q_k = Q_{k,\min} + Round(RS * (Q_{k,\max} - Q_{k,\min}))$$

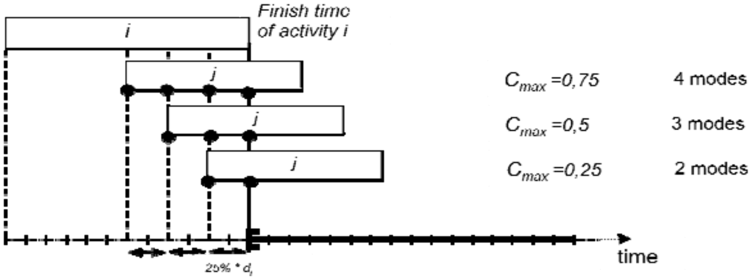
where $Q_{k,min}$ is the minimum acceptable value for the resource *k* availability to complete the project, equal to the maximum resource *k* request per job. $Q_{k,max}$ is calculated as the peak demand of resource *k* in the initial makespan, without resource constraint and with earliest start schedule. Q_k is the resource *k* availability during the whole project. The *RS* factor therefore represents the influence of resource constraints on the project.

In our design of experiment, we fixed a median value for *C* and *RF*, *2.1* and *0.5* respectively, and generated *9* projects with similar network characteristics and resource demand. For each project, three different characteristics of resource availability were created (*RS=1*, *0.75* and *0.5*). Finally, *27* comparable projects without overlap data are generated (*9* for each value of *RS*).

Three additional parameters were considered to generate overlap data. First, we set the factor *R* the percentage of overlappable couples of activities among all couples of dependent activities. This factor illustrates opportunity of overlapping, and reflects a strategy of project execution. Indeed, a project can allow a more or less important number of couples of overlappable activities depending on the nature of the activities and strong or flexible dependency relationship between them. In the literature, some authors present many cases of overlapping situations, considering from *100%* to *10%* of overlappable activities among all couples of activities (Gerk and Qassim, 2008). In order to present different cases encountered in practice, three different values of *R*, *20%*, *40%* and *60%* we here considered.

The second factor C_{max} is the maximum allowable amount of overlap. The value of this factor is determined by activity milestones and previous information needed to start the downstream activity. All overlappable activities were assumed to have similar milestones and the same maximum amount of overlap. In the literature, authors have used various maximum of overlap (Gerk and Qassim 2008; Wang and Lin, 2009). In this paper, three different values of C_{max} were considered: *25%*, *50%* and *75%*, which correspond to a conservative, median and aggressive possibility of overlapping execution, respectively. Figure 2 illustrates the different modes associated to these values.

Figure 2: Possible values of C_{max} and associated modes



The third factor β is the amount of rework per period of overlapping. This amount depends on the nature of the project and its associated risks. This amount, set to a value of 40%, is here considered to be the same for all activities. In practice, the project planner has to determine the amount of rework for each overlappable activity before using an overlapping strategy, but our assumption allows to obtain an upper bound which defines the maximum gain that can be obtained by accelerating development activities through overlapping, and the maximum induced cost.

The three factors, R, C_{max} and β were used to generate overlapping data for each project. Overlappable couples of dependent activities are randomly selected in the list of dependent activities. An opportunity list is established with the highest value of R. Then, for each value of R, a choice is made randomly in this list of couples of activities. The percentage of overlappable couples is equal to the defined value of R. Once the overlappable couples are identified, the overlap mode data is generated, with overlap amount per mode and associated rework.

Table 1 summarizes our design of experiment. The resource strength factor RS, the percentage of overlappable couples of activities among the total couples of dependent activities and the maximum amount of overlapping C_{max}, were all tested at three levels on 9 similar project topologies generated with PROGEN, resulting in 243 projects.

Table 1: Variable parameter levels

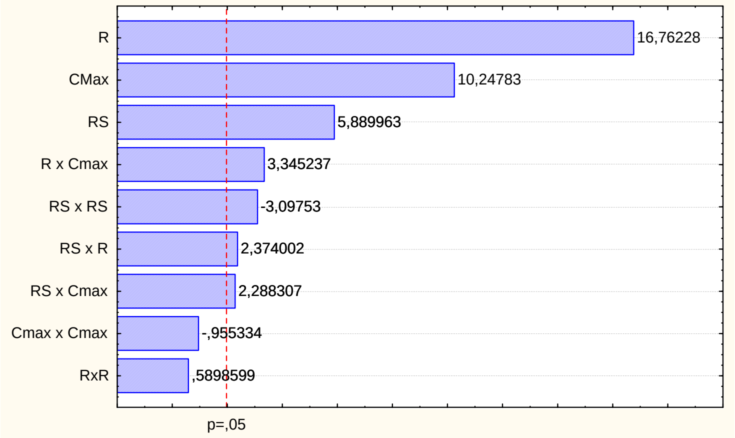
RS	*0.5*	*0.75*	*1*
R	*0.2*	*0.4*	*0.6*
C_{max}	*0.25*	*0.5*	*0.75*

5 Computational results

The 243 generated projects were implemented in AMPL Studio v1.6.j and solved with CPLEX 12.2. Because of overlapping opportunities defined in our data generation procedure, the results in terms of optimal time reduction vary for each project. As each project has a different initial makespan, the effectiveness of overlapping strategy was measured as the percentage of time reduction when comparing the calculated project makespan with overlap with the initial project schedule. Additional costs resulting from rework in also measured in a similar manner. The resource cost is estimated at $100 per period and we considered a $20,000 fixed cost.

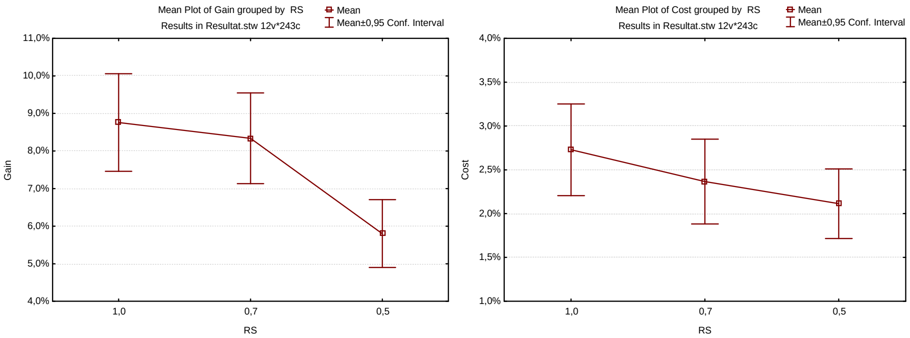
The effects of the different parameters were analyzed by conducting ANOVA. The resulting Pareto chart, presented in figure 3, indicates that the three factors explain *80%* of variation in effectiveness of overlapping in terms of time reduction and cost increase. The chosen factors thus have a significant impact in overlapping effectiveness. We also observed important interaction between the percentage of overlapping opportunities *R* and the maximum allowed amount of overlapping and between the availability of resources and the two other factors. These interactions clearly show the indirect impact of resource constraints on the effectiveness of overlapping as a risk response strategy.

Figure 3: Pareto chart of standardized effects



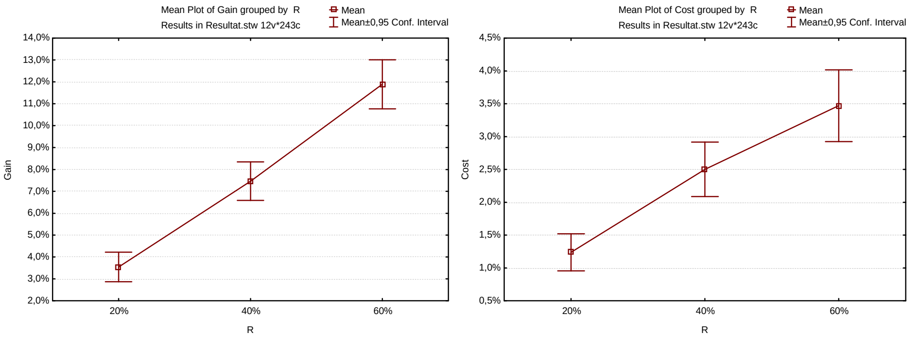
From figure 4, one can see the mean effect of *RS* in the effectiveness of overlapping strategy as a risk response in terms of additional cost and total maximum time reduction. *RS* has a strong impact on effectiveness but is not significant in terms of cost influence. Indeed, the reduction of *RS* decreases the opportunity of overlapping and the resulting time gain. This is due to strong resource constraints reducing overlapping opportunities. The large gap between *RS=0.75* and *RS=0.5*, where the gain varies from *8.8%* to *5.8%* shows the importance of resource constraints and the necessity to take them into account when scheduling projects. Indeed, overlapping increase the impact of resource constraints as concurrent activities may require the same resources at the same time. The time of rework has also an impact on resource constraints as every overlapped activity requires additional labor time due to the addition of rework.

Figure 4: *RS* impact in terms of time reduction and cost



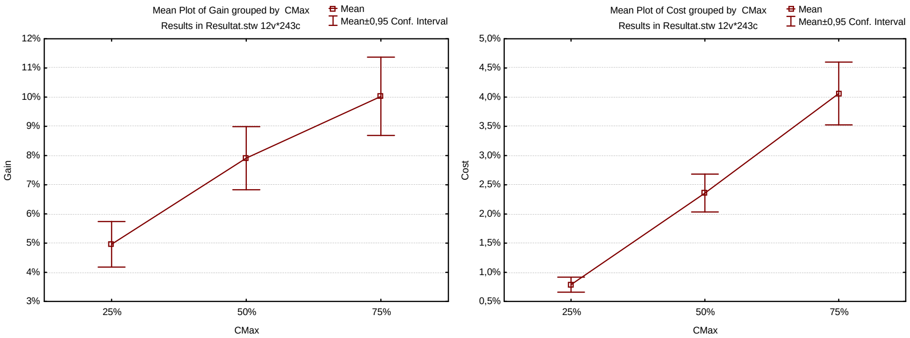
The impact of altering the number of overlapping opportunities R can be seen in figure 5. As R increases, the effectiveness of overlapping increases too, from *2.5%* to almost *12%*. This is due to the numerous overlapping opportunities which allow to bypass many resource constraints and finally to decrease the time of execution of the project. The impact on cost is concave: the greater the number of overlappable couples of activities is, the less important the influence of R on cost is. This can be explained by the increasing number of overlap opportunities which allows small overlapping to be efficient. This point highlights the significance of identifying correctly the couples of overlappable activities in the risk response planning phase.

Figure 5: R impact in terms of time reduction and cost



The increase in the maximum overlapping factor results in a concave increase of gained time (*cf.* figure 6). Significant overlapping modes allow to reduce effectively the time of execution of the project. However, resource constraints tend to reduce the possibilities of major overlapping. On the contrary, the impact on cost seems to be linear from *0.8%* to *4%*. The maximum overlap amount allowed has a direct impact on rework time.

Figure 6: C_{max} impact in terms of time reduction and cost



These computational results show that a high resource level combined with numerous opportunities of overlapping and a high percentage of maximum overlapping favor overlapping to be an efficient risk response strategy when anticipating project delay. The most important factor affecting the effectiveness of overlapping as a risk response strategy is the number of overlappable couples of activities. Resource availability has less direct impact but this factor has a high interaction with the other factors. Finally, the maximum amount of overlapping, as well as its interaction with the number of overlappable couples, is important to be considered when evaluating the effectiveness of overlapping measures.

The most important interaction, between the number of overlappable couples and the maximum amount of overlapping, were further analyzed by studying three scenarios. The first one is a project with many overlappable couples of activities and a low amount of maximum overlapping. The second one is a median one in terms of opportunities of overlapping and of maximum amount of overlapping. The third one is a strategy with few overlappable couples and high amount of maximum overlapping. As shown in Table 2, the first and second strategies are more effective than the third one but the median strategy results in additional cost. This result supports the fact that the number of overlappable activities greatly affects the effectiveness of an overlapping strategy.

Table 2: Mean impact of project characteristics in overlapping effectiveness

R	C_{max}	Time reduction	Cost increase
60%	*25%*	*8.4%*	*1.1%*
40%	*50%*	*8.3%*	*2.4%*
20%	*75%*	*4.6%*	*2.0%*

6 Conclusion

This study shows the influence of three main factors influencing the effectiveness of adopting overlapping as a risk mitigation measure when anticipating project delay in early phases of engineering projects. The percentage of overlappable activities is a predominant factor of effectiveness while having a low impact on additional cost associated with rework. Overlapping effectiveness increases with number of overlappable activities by creating more opportunities to resolve resource constraints, and therefore reducing the total project duration.

The maximum amount of overlapping allowed also impacts the effectiveness of overlapping measures. However, the increase in project time reduction comes with the expense of additional work and costs. Allowing important amount of overlapping must be studied carefully as it may create additional risks for the project.

The impact of resource constraints on the maximum time reduction that can be obtained through overlapping measure is another important result of this study. First, our experimental results show that strong resource constraints greatly reduce the possibilities of overlapping as concurrent activities may require the same resources and thus, creating resource conflicts that can be only resolved by delaying some activities. Consequently, overlapping activities may in some cases have no impact in total project duration. In addition, our results demonstrate that the potential benefits of overlapping measures vary greatly from one project to another. Even when comparing similar projects, the maximum gain in time reduction depends on the characteristics of the initial project schedule. This result demonstrates the usefulness of the proposed approach which relies on a project scheduling model.

We can also conclude that defining risk response strategies relying solely on historical data from previous projects is not sufficient to adopt an adequate risk response plan. Risk mitigation measures must be assessed by analyzing the impact of project resources. Historical data are however useful by proving insights when determining the maximum amount of overlap that should be allowed and by estimating the amount of rework associated with overlapping.

We would like also to point out some limitations of the proposed approach and suggest possible directions for future research. First, our approach relies on an optimal scheduling model. As in most resource scheduling approaches, computation time is an issue when analyzing real projects. In our experiments, the number of overlapping modes has an important impact on computational time, tending to make impossible the implementation of this upper bound analysis in practice. Future works could develop heuristics or meta-heuristics to compare the effectiveness of different risk response strategy as overlapping.

Secondly, we considered the impact of overlapping on total project duration and assumed that the inherent risks of this measure can be simply taking into accounts by considering rework and its related cost. In practice, adopting overlapping may face other risk elements, as exposed in the concurrent engineering literature (Kayis et al., 2006). These elements must be analyzed as well.

Finally, our model calculates the maximum gain of overlapping measures from a discrete point of view. A stochastic approach could offer a satisfactory estimation of effectiveness of overlapping, rather than an upper bound. We have also to mention that the calculated upper bound is only feasible at the beginning of the project. As the project progress, this maximum gain decreases. A project rescheduling approach should be adopted within the risk control activities to continuously assess the effectiveness of overlapping as a valid measure to respond to project delay.

References

Berthaut, F, Grèze L, Pellerin, R, Perrier, N & Hajji A 2011, 'Optimal resource-constraint project scheduling with overlapping modes', submitted for *International Conference on Industrial Engineering and Systems Management*.

Bogus, SM, Molenaar, KR & Diekmann, JE 2005, 'Concurrent engineering approach to reducing design delivery time', *Journal of Construction Engineering and Management*, vol. 131, no. 11, pp. 1179–1185.

Bogus, SM, Molenaar, KR & Diekmann, JE 2006, 'Strategies for overlapping dependent design activities', *Construction Management and Economics*, vol. 24, pp. 829–837.

Browning, TR & Eppinger, SD 2002, 'Modeling impacts of process architecture on cost and schedule risk in product development', *IEEE Transactions on engineering management*, vol. 49, no. 4, pp. 428–442.

Chapman, C 1997, 'Project risk analysis and management – PRAM the generic process', *International Journal of Project Management*, vol. 15, no. 5, pp. 273–281.

Chen, CH, Ling, SF & Chen, W 2003, 'Project scheduling for collaborative product development using DSM', *International Journal of Project Management*, vol. 21, pp. 291–299

Cho, SH & Eppinger, SD 2005, ‘A simulation-based process model for managing complex design projects’, *IEEE Transactions on engineering management*, vol. 52, no. 3, pp. 316–328.

Choi, HG & Ahn, J 2010, ‘Risk analysis models and risk degree determination in new product development: A case study’, *Journal of Engineering and Technology Management*, vol. 27, pp. 110–124.

Clark, KB & Fujimoto, T 1991, *Product development performance strategy, organization and management in the world auto industry*, Harvard Business School Press, Boston, MA.

Cooper, DF, Greay, S, Raymon, G & Waler, P 2005, *Project risk management guidelines: Managing risk in large projects and complex procurements*, Jown Wiley and Sons, Ltd.

Gerk, JEV & Qassim, RY 2008, ‘Project acceleration via activity crashing, overlapping, and substitution’, *IEEE Transactions on Engineering Management*, vol. 55, no. 4, pp. 590–601.

Kayis, B, Arndt, G, Zhou, M, Savci, S, Khoo, YB & Rispler, A 2006, ‘Risk Quantification for New Product Design and Development in a Concurrent Engineering Environment’, *CIRP Annals - Manufacturing Technology*, vol. 55, no. 1, pp. 147–150.

Kolisch, R, Sprecher, A & Drexl, A 1992, ‘Characterization and generation of a general class of resource-constrained project scheduling problems - Easy and hard instances’, Research Report 301, Institut für Betriebswirtschaftslehre, Christian-Albrechts-Universität zu Kiel

Krishnan, V 1996, ‘Managing the simultaneous execution of coupled phases inconcurrent product development’, IEEE Transactions on Engineering Management, vol. 43, no. (2), pp. 210–217

Krishnan, V, Eppinger SD & Whitney DE 1997, ‘A model-based framework to overlap product development activities’, *Management Science*, vol. 43, no. 4, pp.437–451.

Lin, J, Chai, KH, Brombacher, AC & Wong, YS 2009, ‘Optimal overlapping and functional interaction in product development’, *European Journal of Operational Research*, vol. 196, no. 3, pp. 1158–1169.

Lee, E, Park, Y, & Shin, JG 2009, ‘Large engineering project risk management using a Bayesian belief network’, *Expert Systems with Applications*, vol. 36, pp. 5880–5887.

Patterson, FD & Neailey, K 2002, ‘A risk register database system to aid the management of project risk’, *International Journal of Project Management*, vol. 20, no. 5, pp. 365–374.

Roemer, TA, Ahmadi, R & Wang, RH 2000, ‘Time-cost trade-offs in overlapped product development’, *Operations Research*, vol. 48, no. 6, pp. 858–865.

Sabbagh, K 1996, *Twenty-first century jet*, Scribner, New York.

Smith, PG & Merritt, GM 2002, *Proactive Risk Management: Controlling Uncertainty in Product Development*, Productivity Press, New York.

Smith, P & Reinertsen, D 1995, *Developing Products in Half the Time*, New York: Van Nostrand Reinhold.

Smith, PG & Reinertsen, DG 1998, *Developing Products in Half the Time*, 2nd edn. John Wiley, New York.

Steward, DV 1981, ‘The design structure system: a method for managing the design of complex systems’, *IEEE Transactions on Engineering Management*, vol. 28, pp. 71–74.

Terwiesch, C & Loch, CH 1999, ‘Measuring the effectiveness of overlapping development activities’, *Management Science*, vol. 45, no. 4, pp. 455–465.

Wang, JT & Lin, YI 2009, ’An overlapping process model to assess schedule risk for new product development’, *Computers & Industrial Engineering*, vol. 57, no. 2, pp. 460–474.

Williams, T 1995, ‘A classified bibliography of recent research relating to project risk management’, *European Journal of Operational Research*, vol. 85, no. 1, pp. 18–38.

Annex: The linear 0-1 integer program

Table 1: Symbols and definitions

Symbol	Definition
S	Set of activities
n	Number of non-dummy activities
$E = A \cup P$	Set of temporal or precedence constraints
$i \rightarrow j\ (i, j)$	Precedence constraint
d_j	Processing time of activity *j*
A	Set of couples of overlappable activities
P	Set of couples of non-overlappable activities
$A(j)$	Set of immediate predecessors of activity *j* that are overlappable with activity *j*
$P(j)$	Set of immediate predecessors of activity *j* that are not overlappable with activity *j*
$Pred(j) = A(j) \cup P(j)\ \forall j \in S$	Set of immediate predecessors of activity *j*
R	Set of renewable resources
R_k	Constant amount of available units of renewable resource *k*
R_{jk}	Per period usage of activity j of renewable resource *k*
m_j	Number of execution modes of activity *j*
α_{ijm}	Amount of overlap duration between activities *i* and *j* in execution mode *m*, expressed as a fraction of d_j
r_{jm}	Expected amount of rework in activity *j* in execution mode *m*
T	Upper bound of the project's makespan
$t = 0,..,T$	Periods
EF_j	Earliest possible finish time of activity *j*
LF_j	Latest possible finish time of activity *j*

Each activity *j* must finish within the time window $\{EF_j,...,LF_j\}$ with respect to the precedence relations and the activity durations. They can be derived from the traditional forward recursion and backward recursion algorithms considering that the project must start at time *0* and that *T* constitutes an upper bound of the project makespan (*i.e.* the sum of processing times of all activities) (Hartmann, 1999). We define the decision variables (*i.e.* the finish times and the overlapping modes) as follows:

$$X_{jtm} = \begin{cases} 1 & \text{if activity } j \text{ is executed in mode } m \text{ and finished at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$\forall j \in S\,,\ \forall t \in [0,T] \text{ and } \forall m \in [1, m_j] \qquad (1)$$

The decision on the activity modes can be classed into three cases. On the one hand, if activities (*i*,*j*) are not overlappable, the decision is simply not to overlap. On the other hand, if activities (*i*, *j*) are overlappable, these activities can be either overlapped (*m > 1*) or executed in series (*m=1*). The resource-constrained scheduling problem with overlapping can then be formulated as a linear 0-1 integer program as follows: Minimize $\sum_{m=1}^{m_{n+1}} \sum_{t=EF_{n+1}}^{LF_{n+1}} t \cdot X_{n+1,t,m}$ (2)

Subject to:

$$\sum_{m=1}^{m_i} \sum_{t=EF_i}^{LF_i} t \cdot X_{itm} \le \sum_{m=1}^{m_j} \sum_{t=EF_j}^{LF_j} \left(t - d_j \cdot (1-\alpha_{ijm}) - r_{jm}\right) \cdot X_{jtm} \qquad \forall j \in S\,, \forall i \in Pred(j) \qquad (3)$$

$$\sum_{m=1}^{m_j} \sum_{t=EF_j}^{LF_j} \alpha_{ijm} \cdot X_{jtm} \le Y_{ij} \qquad \forall j \in S\,, \forall i \in A(j) \qquad (4)$$

$$\sum_{m=1}^{m_i} \sum_{t=EF_i}^{LF_i} t \cdot X_{itm} \ge \left(\sum_{m=1}^{m_j} \sum_{t=EF_j}^{LF_j} \left(t - d_j (1-\alpha_{ijm}) - r_{jm}\right) \cdot X_{jtm} \right) - T \cdot (1 - Y_{ij}) \qquad \forall j \in S\,, \forall i \in A(j) \qquad (5)$$

$$\sum_{j=2}^{n} \left[R_{jk} \cdot \left(\sum_{m=1}^{m_j} \sum_{b=t}^{t+d_j-1+r_{jm}} X_{jbm} \right) \right] \le R_k \qquad \forall k \in R \ \ \forall t \in [1,T] \qquad (6)$$

$$\sum_{m=1}^{m_i} \sum_{t=EF_i}^{LF_i} t \cdot X_{itm} \le \sum_{m=1}^{m_j} \sum_{t=EF_j}^{LF_j} t \cdot X_{jtm} \qquad \forall j \in S\,, \forall i \in A(j) \qquad (7)$$

$$\sum_{m=1}^{m_j} \sum_{t=EF_j}^{LF_j} X_{jtm} = 1 \qquad \forall j \in S \qquad (8)$$

$$X_{jtm} \in \{0,1\} \qquad \forall j \in S\,,\ \forall t \in [0,T] \text{ and } \forall m \in [1, m_j] \qquad (9)$$

$$Y_{ij} \in \{0,1\} \qquad \forall j \in S\,, \forall i \in Pred(j) \qquad (10)$$

The objective (2) minimizes the finish time of the dummy sink activity and therefore, the project makespan. Constraint (3) represents the finish-to-start precedence constraints, with a negative lead time in the case of overlapping. According to constraints (4), if two overlappable activities (*i*,*j*) are overlapped, then $Y_{ij} = 1$. If activities (*i*,*j*) are not overlapped, then Y_{ij} is unrestricted and constraints (5) are not restrictive.

Constraints (6) define the resource constraints. Constraints (7) guarantee that the downstream activity of a couple of overlappable activities can not finish before the upstream activity finish time. Constraints (8) ensure that each activity is assigned one activity mode and one finish time. Finally, constraints (9) and (10) define the aforementioned binary decision variables.