Degree of Overlapping Design Activities in Vehicle Development : A System Dynamics Approach

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Abstract

The vehicle development process (VDP) is iterative in nature with numerous interactions and information flows between design groups and between development phases. The VDP has been changed from a sequential-functional development to a concurrent-team based approach. Concurrent execution of design activities may reduce the development lead-time, but it increases the managerial complexity in the VDP. A system dynamics model was developed to understand the transient behavior of parallel, overlap, and sequential processes in the VDP and to determine the optimal level of overlapping considering the development lead-time and total number of reworks. The simulation results showed that different execution processes should be used, depending upon the intensity of reworks.

Key Words: System Dynamics, Simulation, Vehicle Development Process, Parallel, Sequential and Overlap Process.

1. Introduction

The VDP is complex and iterative in nature. It is characterized by numerous tasks that are linked, grouped into phases, and executed by functional and physical design groups, through which the concepts, requirements, and technical specifications are generated, validated, and finalized (Krishnan, 1996; Clark, and Fujimoto, 1991). Several changes have been introduced in the VDP in order to reduce development lead-time: concurrent engineering, design for manufacturing, cross-functional approach, computer-aided-engineering, etc. One of these changes is the shift from the traditional sequential-functional development, to a concurrent-team based paradigm.

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The benefits of concurrent engineering are recognized in a large number of articles (Imai *et al.*, 1985; Takeuchi and Nonaka, 1986; Wheelwright and Clark, 1992). Despite its success, there is recent evidence that concurrency is not applicable to all product development projects (Eisenhardt and Tabrizi, 1995; Terwiesch *et al.*, 1996; Loch and Terwiesch, 1998). Greater concurrence and cross-functional development may reduce the development lead-time, but they dramatically increase the complexity of the VDP in the areas of information flow, communication, coordination, etc (Krishnan *et al.*, 1995). Often, simultaneous execution of design activities results in increased design duration and rework in the absence of proper management, because of the interdependent nature of designing a vehicle (Ford, 1995).

Blackburn (1991) emphasized the importance of reducing redesigns and thus reworks. He stated that product redesign is "a major cause of long lead-times in development cycles." Krishnan (1996) presented a framework and an optimization model to manage the risks involved in the simultaneous execution of coupled development phases. Clark *et al.* (1991) presented a framework to integrate problem-solving cycles in the VDP. They distinguished between the timing of action and communication patterns that exist between the upstream and downstream groups. They recommended stage overlapping, face-to-face communication, piece-by-piece information release, bilateral communication, and early release of preliminary information. Also, it was recommended to overlap the product and process stages with early downstream involvement and information exchange without executing the designs, prior to problem-solving cycles, in order to reduce lead-time. Ha *et al.* (1995) developed a model for the optimal review periods and analyzed the effects of changing the timing of design reviews on the total length of the development process. However no, research has been done in order to analyze the dynamic and transient behavior of parallel, overlap, and sequential processes and to determine the optimal degree of overlap by applying the system dynamics approach in the VDP.

The purpose of this paper is to understand the transient behavior of parallel, overlap, and sequential processes in the VDP, and to determine the optimal degree of overlap in terms of lead-time and total reworks. What we observed in the vehicle development process is that, because of the ever-increasing pressure to reduce lead-time, parallel execution is encouraged even before critical requirements and technical information are mature enough. Designs are executed as early as possible in order to have buffer time to fix problems (fire fighting) because it is well known that there will be unexpected problems. System dynamics was used for this research, which has been successfully applied in analyzing the interdependent activities in product development such as human resource acquisition and allocation, scheduling, project scope, manufacturing, finance, and marketing interactions (Ford, 1995; Cooper, 1993; Richardson and Alexander, 1981; Roberts, 1974).

The remainder of this paper is organized as follows: sequential, overlap, and parallel processes are briefly explained in section 2. An overview of the VDP is discussed in section 3, and the system dynamics model is briefly explained in section 4. Several scenarios are analyzed in section 5, and a summary follows.

2. Parallel, Overlap, and Sequential Processes

Three types of processes are shown in Figure 1. parallel, overlap, and sequential execution of design processes. In a parallel process, Under Body and Upper Body designs are executed at the same. This type of execution reduces the time delays involved in exchanging design information and promotes frequent communication and teamwork. The early release of design information enables the early detection of rework. However, since many engineering characteristics are considered at the same time, engineers have to juggle many factors simultaneously, which causes confusion and consequently demands more resources.

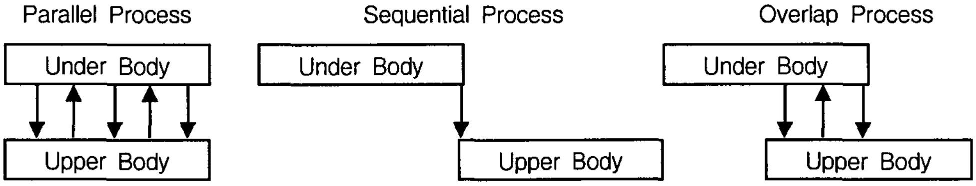

Figure 1. Parallel, overlap, and sequential execution of design process in the VDP

In a sequential execution, the Upper Body design can be executed only after all Under Body designs are accomplished. Design information is released in a batch mode to downstream design groups. The sequential execution of design activities is a step-by-step process and it is easy to understand and manage neighboring design activities. However, the progress of downstream designs is greatly dependent upon the quality of upstream design activities. If the downstream design groups find that some designs released from the upstream design groups are infeasible for various reasons, then the upstream design groups have to revise the infeasible designs, which create rework for the downstream design groups. The time delay in discovering rework and the lack of communication are the main causes of the schedule- and cost-overruns in the "throw-over-the-wall" approach (Ford, 1995; Cooper, 1993).

The downstream design activities in the overlap process start their designs only after certain progress has been made in the upstream design activities. For example, once the Under Body group finishes sixty percent of its designs, the Upper Body group starts the execution of its designs. This process has several benefits, such as avoiding unnecessary delays in design information exchange, over-design, and unnecessary design iterations due to the use of premature design information.

3. Overviews of the Vehicle Development Process

The complex interactions and inter-dependencies among major subsystem designs in the VDP are shown in Figure 2. The thick lines indicate the flow of requirements and design information, while the thin lines show feedback between major subsystems. Power-train and Wheel/Tire drive the design of the Under Body, which, in turn, drives Upper Body design, which restricts the design of the Instrument Panel (I/P), Interior, and Exterior.

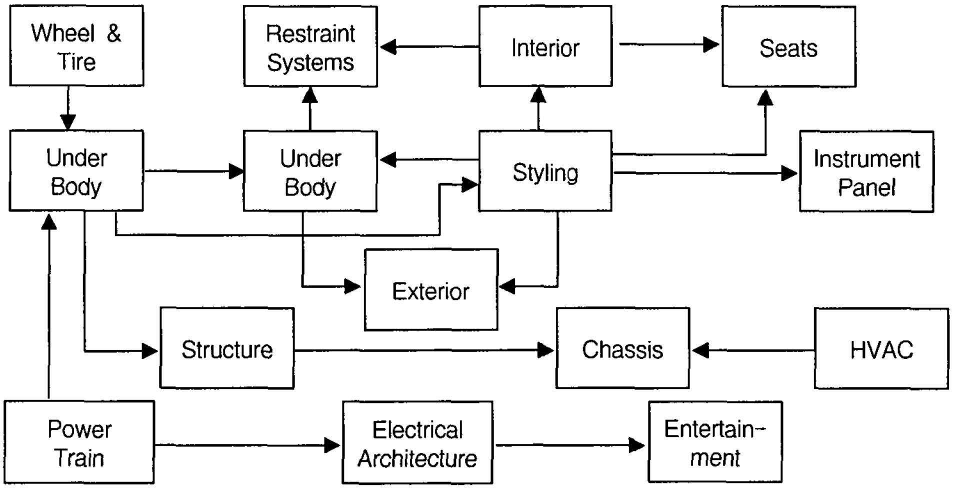

Figure 2. Major information flow in the VDP

The coupled interactions and information-flow indicate that design changes and rework have direct and indirect cascading effects depending on various time delays. For example, a design change in the Under Body has a direct impact on the Chassis, Upper Body, and Styling, and an indirect impact on the Electrical, I/P, Exterior, and Interior designs, which usually are not under the Under Body engineer's control and are not necessarily the Under Body engineer's concern. The indirect impacts are not usually evident until after long time delay. The cascading effect of design changes or rework generates confusion in the VDP and thus requires additional resources and effort for coordination and integration.

From this information, a simplified flow of major subsystem design in the VDP was derived by applying the Design Structure Matrix (Steward, 1981; Eppinger, 1991; Kusiak and Wang, 1993) as shown in Figure 3. This diagram was selected to illustrate our research purpose and does not represent the VDP in an automotive manufacturer. The VDP in figure 3 consists of ten major subsystems in four overlapping stages. The major subsystems in each stage are: (1) First stage: Power-train and Wheel & Tire requirements determination, (2) Second stage: Under Body and Chassis designs (3) Third stage: Upper Body and Styling designs, (4)

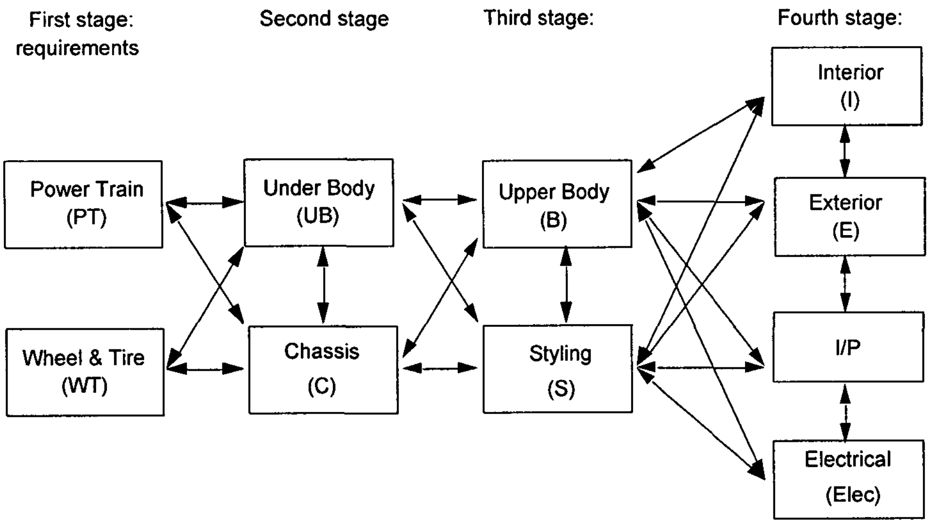

Figure 3. A view of the VDP with ten major subsystems in four stages

Fourth stage: Electrical, I/P, Exterior, and Interior designs

Power-train and Wheel/Tire in the first stage represent the determination of requirements. The requirements are released to the Under Body and Chassis groups in the second stage. The Upper Body and Styling groups in the third stage, have the most frequent interactions with the rest of the major subsystems.

The structure of major subsystems in the lower part is identical to the upper part in Figure 3 in terms of information flow and overlapping in the analysis. For this paper, only the behavior of the upper portion of the major subsystems will be shown and can easily be identified.

4. System Dynamics Model

The System Dynamics model shown in Figure 4 was developed based on the previous models (Ford, 1995; Cooper, 1993) brilliantly showed that undiscovered rework is the main cause of cost and schedule overruns and developed the concept of the *rework cycle*. He analyzed how management policies such as resource acquisition and allocation, scheduling adjustment, and overtime have undesirable effects on project performance. Ford (1995) developed a model capturing the internal and external precedence relationship for tasks and stage overlapping respectively. Rodrigues *et al.* (1996) provided a comprehensive review on the application of system dynamics in project management.

Assume that the Upper Body group has one hundred design tasks to perform. The tasks could

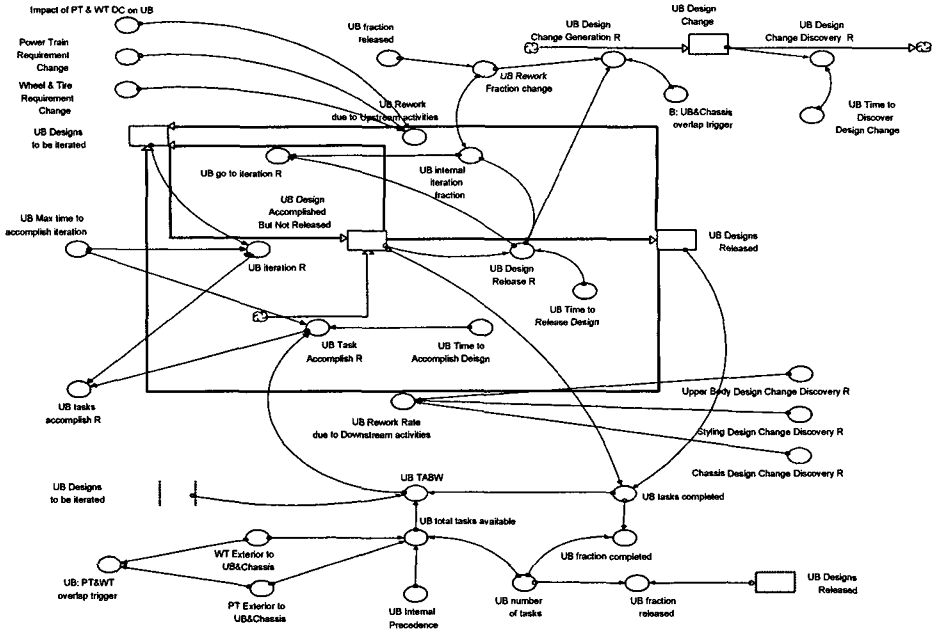

Figure 4. Interactions among major subsystems

be drawings, analytical models, or components in the Upper Body design. These tasks are completed and then reside in the box named "design tasks accomplished." If the accomplished tasks are satisfactory, then they are flow into the box named "designs tasks accomplished and released." If they are not satisfactory, then the tasks have to be performed again by going through an internal design iteration loop.

Once sufficient design tasks are accumulated in the "designs tasks accomplished and released," the Exterior group starts executing its own designs, depending on the overlap triggering mechanism. After some time delay, if the Upper Body group makes design changes because of requirement changes, technologically infeasible designs, or new technology adoption, the changed design information is conveyed to the Exterior group, thus creating rework for them also. The unsatisfactory designs in the Upper Body have to be withdrawn from the "designs tasks accomplished and released" and go through the external design iteration. Once the Exterior group performs its designs, it discovers unexpected problems, which have to be solved by the Upper Body group. This creates more rework in the Upper Body group, again reducing the level of "design tasks accomplished and released."

A similar information-feedback structure is applied to all other major subsystems and is used as a building block to model the interdependent nature of the VDP. The symbol (||) indicates the time delay involved in the information flow. The formulations for internal and external rework generated are as follows:

- External rework generation rate = Design tasks release rate * external rework fraction
  (tasks/week) (tasks/week) (dimensionless)
- Internal rework generation rate = Design tasks release rate * internal rework fraction
  (tasks/week) (tasks/week) (dimensionless)

4.1 Overlap Triggering

The triggering mechanism to initiate the overlap process is shown in Figure 5. The sixty percent progress triggering indicates that once sixty percent of the Under Body designs are accomplished, the Upper Body designs start. Zero and ninety five percent progress triggering indicate the parallel and sequential processes respectively.

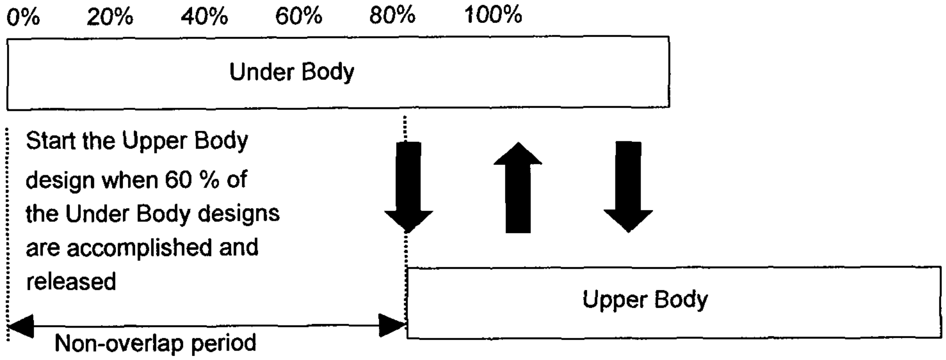

Figure 5. Sixty percent upstream progress triggering mechanism

The rework or design changes generated in upstream designs during the non-overlapped period do not cause rework or design changes in downstream designs. Therefore, simultaneous execution (parallel process) of designs in the Under and Upper Body increases the risk of handling all the rework generated from the beginning. In sequential execution, because the downstream designs wait until ninety five percent of designs in the upstream design are accomplished (this gives a chance of over-design), the rework is quite low but the non-overlap period is usually too long. If infeasible designs are discovered, it will further delay the design progress. Therefore, there are trades-off between earlier execution of designs, which causes much rework and late execution of designs, which causes a long waiting time.

4.2 Scenarios Analyzed

A series of simulations were performed by varying degree of overlap from zero to ninety-five percent, in steps of twenty percent, under three different rework fractions, as shown in Figure 6. The figure shows that the generated reworks are a function of design tasks accomplished and released: initially there are high reworks but as the project makes progress, the reworks are reduced. The three different levels of the rework fraction are as follows: (1) The rework fraction is high (on average 20%), (2) The rework fraction is medium (on average 15%), (3) The rework fraction is low (on average 10%).

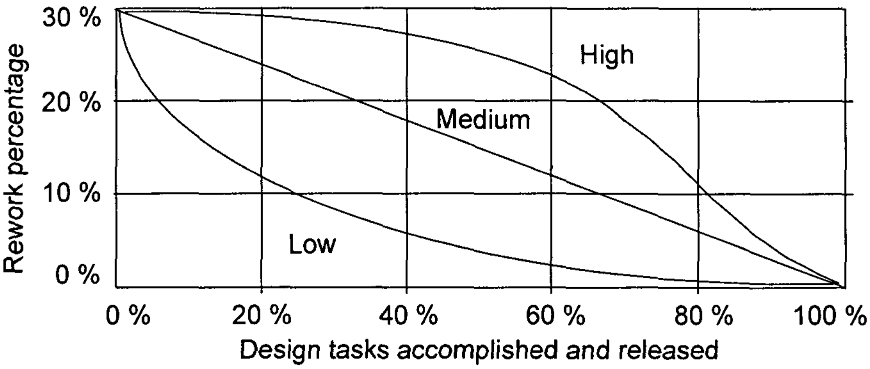

Figure 6. Rework percentage vs. design tasks accomplished and released

4.3 Inputs and Initial Values

All the initial values and input variables are for illustration purposes only, and do not represent an actual automotive manufacturer. All new major subsystems have one hundred design tasks to accomplish, so there are one thousand tasks to accomplish in total. Since major subsystems are not equally difficult to design (e.g., Under Body is more difficult to design than I/P), the relative difficulty of designing major subsystems can be represented by either changing the total number of tasks to do or the rework fraction. Also, the relative impact of a design change is considered (e.g., a design change in Under Body has more impact

Table 1. Relative impacts of a rework.

From\To	PT	WT	UB	C	B	S	I/P	I	E	Elce
Power Train (PT)			1.5	1.5						
Wheel & Tire (WT)			1.5	1.5						
Under Body (UB)	0.25	0.25		1	1					
Chassis (S)	0.25	0.25	1		1	1	1	1	1	1
Upper Body (B)			1	1		1	1	1	1	1
Styling (S)			1	1	1		1		1	1
Instrumental Panel (I/P)					0.5	0.5			1	
Interior (I)					0.5	0.5				
Exterior (E)					0.5	0.5	1	1		
Electrical (Elce)					0.5	0.5	1			

than one in I/P) as shown in Table 1. The Table 1 indicates that one design change in Power-train will generate 1.5-design tasks in Under Body.

5. Simulation Results

5.1 Development Lead-time and Total Rework

The lead-time for the various overlaps with high, medium and low rework fractions is shown in Figure 7. As shown in Figure 7, for the high rework fraction, execution of downstream designs when forty to eighty percent of upstream designs are accomplished and released gives the shortest lead-time. Either parallel or sequential processes have longer development lead-time.

The total number of rework generated from the three different levels of rework fractions, while varying the degree of overlap, is shown in Figure 8. As the degree of overlap increases, the total number of rework also increases. A significant decrease in the total number of rework occurs after the twenty percent upstream progress triggers the downstream design. For the low rework fraction, the degree of overlap does not greatly affect the total number of rework tasks.

The simulation results indicate that if the impact of rework is not critical, parallel execution should be applied. Therefore, if a parallel process is encouraged, even though the impact of rework or rework fraction are high, it will deteriorate the performance of the design progress in terms of lead-time. Otherwise, the overlap process should be applied, and this model can help to determine the time to start downstream designs.

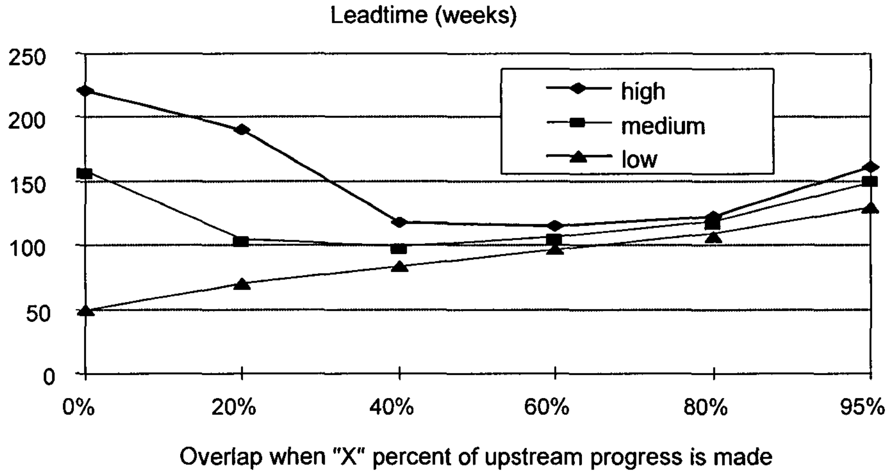

Figure 7. Lead-times for high, medium, and low rework fractions

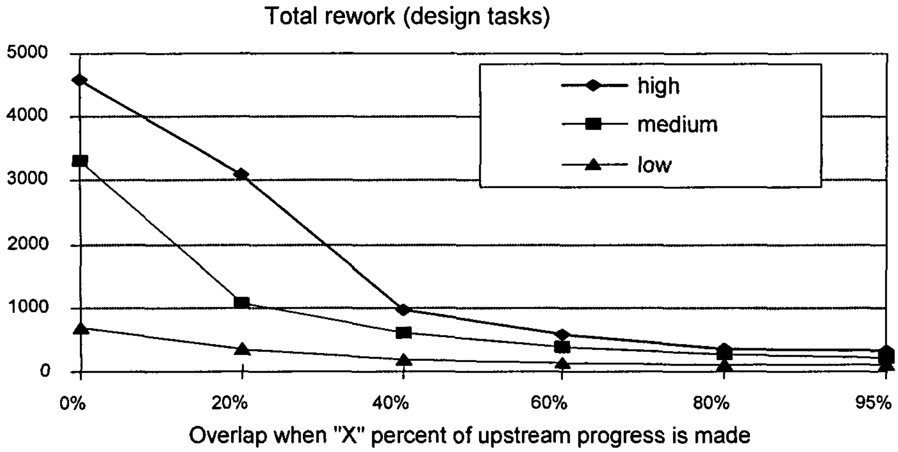

Figure 8. The total rework for high, medium, and low rework fractions

5.2 Designs Accomplished and Released

The progress of major subsystems in parallel execution is shown in Figure 9. Upper Body shows a severely stagnated progress, followed by the Under Body and the Exterior. The Upper Body has the highest number of interactions, as shown in Figure 3, followed by the Under Body and the Exterior designs. The Upper Body does not make any progress until 100 weeks, since the rate of design changes and rework generated from other major subsystems is much higher than the rate at which the Upper Body accomplishes and releases design tasks. Power-train shows the most progress because it has the lowest number of interactions. The stagnated progress of the Under Body, Upper Body, and Exterior are over-exaggerated, but the stagnated progress of Upper Body and Under Body has been observed in many vehicle development programs.

The progress of major subsystems when twenty percent of upstream design progress triggers downstream designs is shown in Figure 10. The Under Body makes smooth progress until the Upper Body starts the execution of its designs. Because of the rework from the Upper Body, the Under Body progress is slightly dampened, but then it regains progress. The Under Body progress shows a similar dampening when the four major subsystems start their designs. However there is a big difference between zero percent upstream design triggering overlap and twenty percent upstream design progress triggering overlap.

There is no great difference in the behavior of the progress of the major subsystems with forty, sixty and eighty percent upstream progress triggering overlaps, as shown in Figure 11 through Figure 13. All the major subsystems show a smooth progression. The designs accomplished and released with ninety-five percent upstream progress triggers downstream designs, is shown in Figure 14. All major subsystems at each stage are engaged in the design once ninety-five percent of upstream designs are accomplished and released. However, only a few design changes and rework will prohibit the completion of the Upper Body designs as the Interior, Exterior, I/P and Electrical subsystems interact and create rework between them and the Upper Body. This shows the negative aspects of the traditional, over-the-wall approach, showing the ninety percent syndrome.

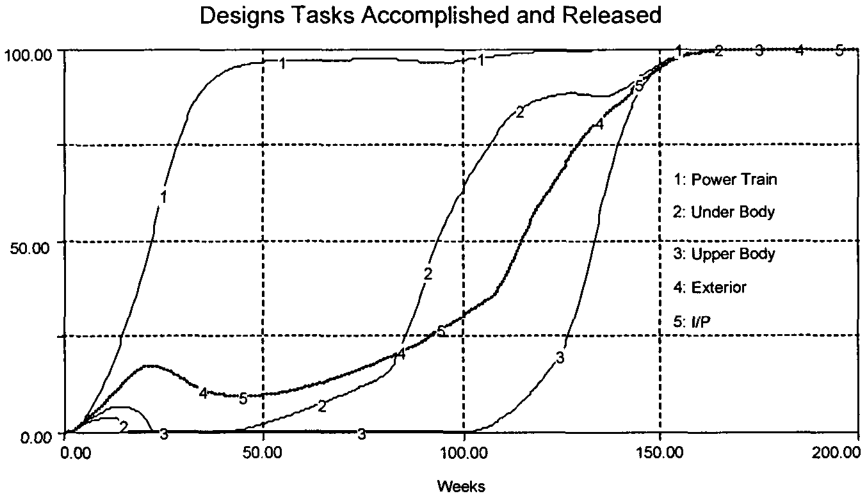

Figure 9. Design tasks accomplished and released with 0% upstream progress triggers downstream design

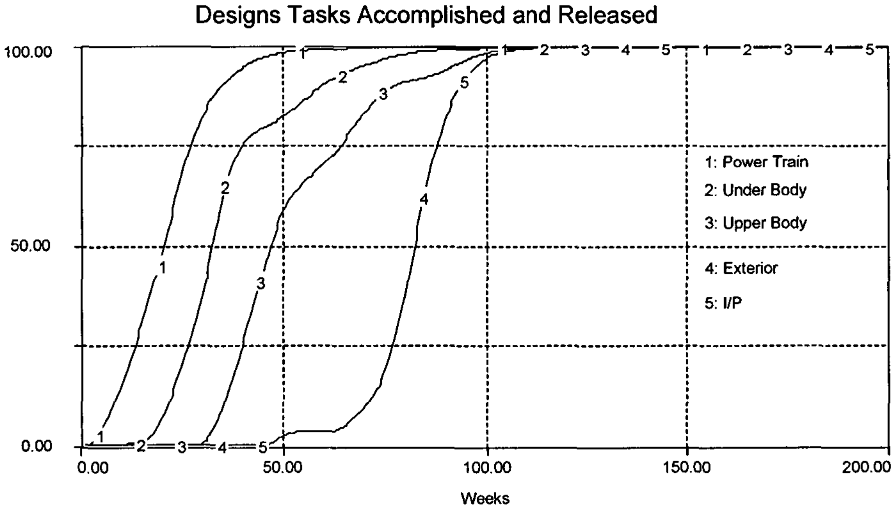

Figure 10. Design tasks accomplished and released with 20% upstream progress triggers downstream design

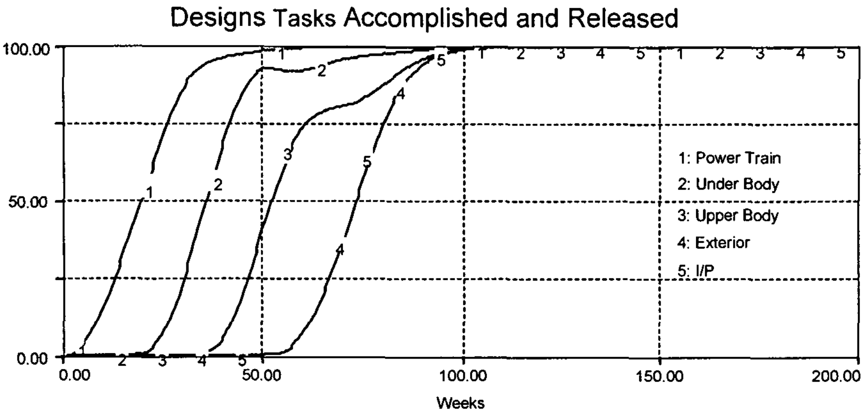

Figure 11. Design tasks accomplished and released with 40% upstream progress triggers downstream design

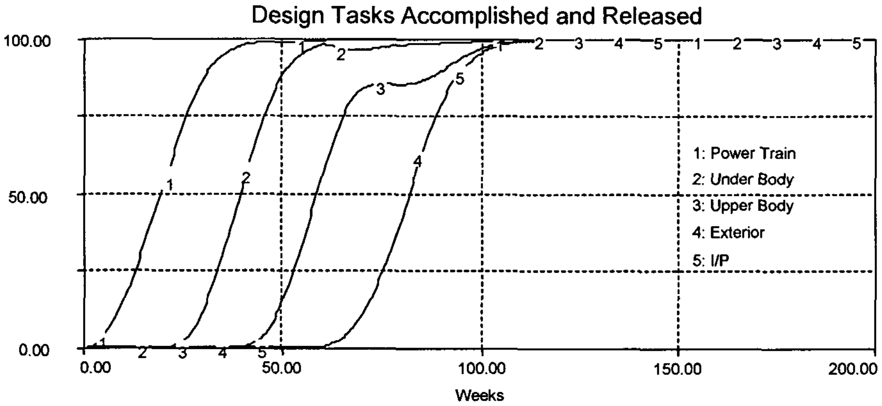

Figure 12. Design tasks accomplished and released with 60% upstream progress triggers downstream design

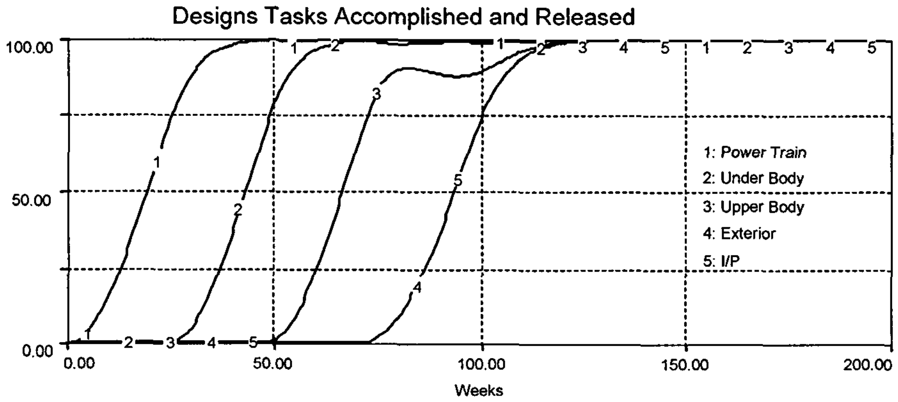

Figure 13. Design tasks accomplished and released with 80% upstream progress triggers downstream design

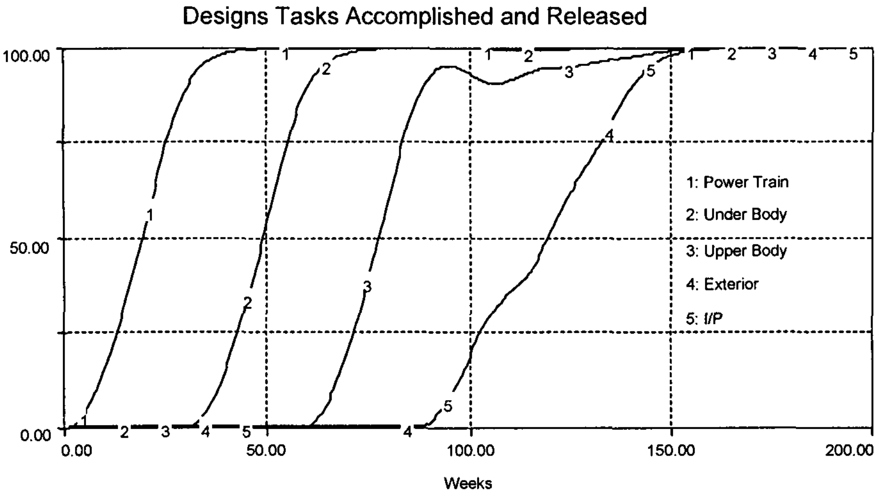

Figure 14. Design tasks accomplished and released with 95% upstream progress triggers downstream design

5.3 Tasks Accomplishment Rate and Resource Allocation

The parallel, overlap, and sequential processes have different meanings for resource allocation. The task accomplishment rates for zero, sixty, and ninety-five percent upstream progress triggering overlap is shown in Figure 15, Figure 16, and Figure 17, respectively. The graphs in this section should be compared with the graphs in section 5.2. The task accomplishment rate contains the task accomplishment rate for the base tasks and internal design iteration rate.

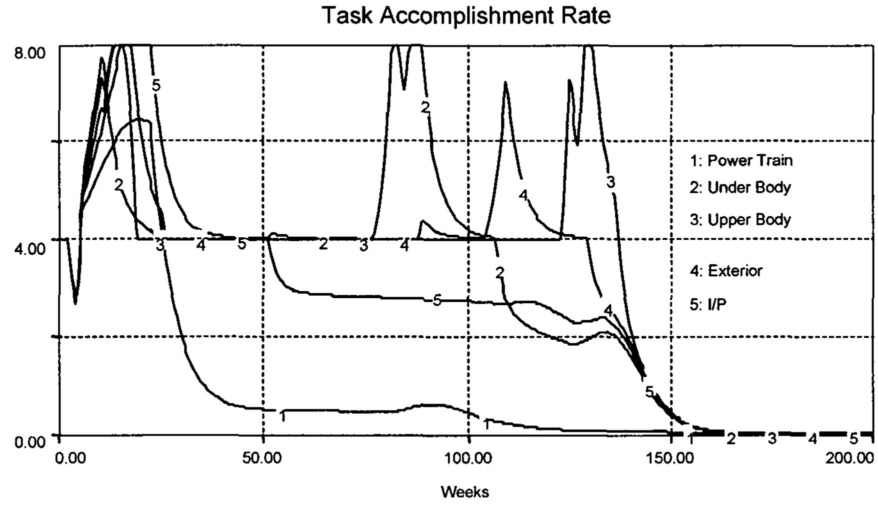

Figure 15. Task accomplishment rate with 0% upstream progress triggers downstream designs

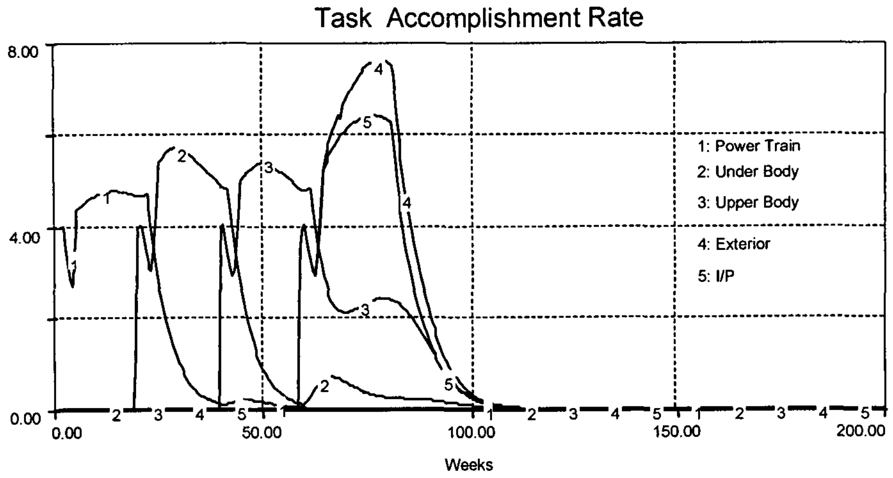

Figure 16. Task accomplishment rate with 60% upstream progress triggers downstream designs

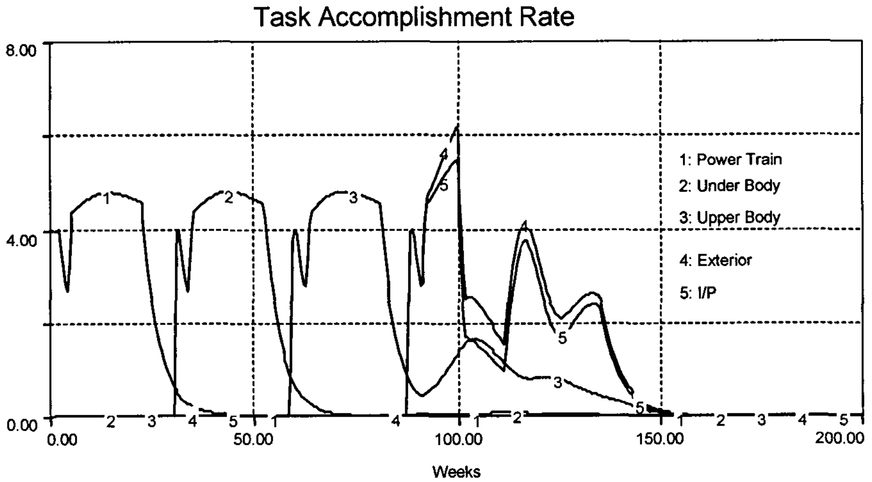

Figure 17. Task accomplishment rate with 95% upstream progress triggers downstream designs

In a sequential execution of design activities, there are unused resources around 25, 60, and 90 weeks, as shown in Figure 17. The sixty percent upstream progress triggering overlap process shows a more uniform distribution of resource utilization, as shown in figure 16.

Because of the need to reduce vehicle development lead-time, an early start of design is attempted. This forces engineers to work on incomplete requirements or designs. Since the engineers work on incomplete requirements or designs, rework is generated, which further delays the schedule. Even though the engineers start their designs as early as possible, the schedules are delayed further. This encourages the engineers to start even earlier in the next stage, so that they will have some buffer time to handle the rework problems. This self-fulfilling prophecy, as shown in Figure 18, has been observed in other new product development cycles (williams *et al.*, 1995). Some research shows that later engagement in designing and construction can significantly reduce lead-time.[21]

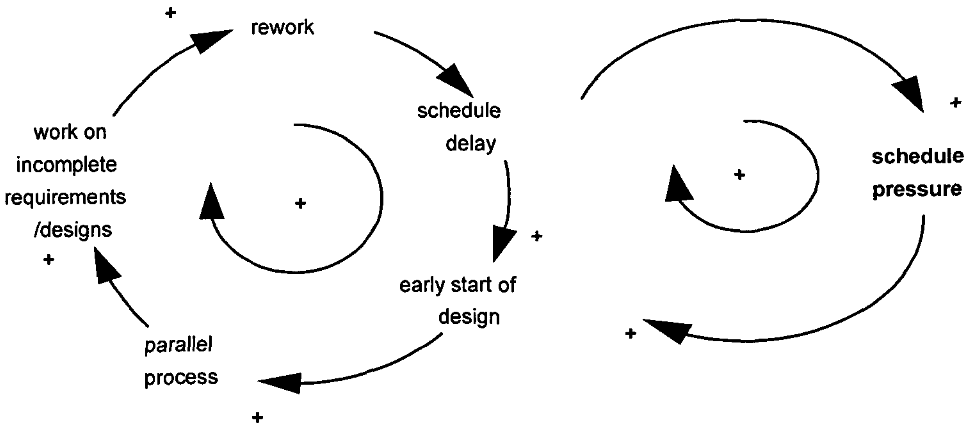

Figure 18. Potential vicious circles of parallel execution

As seen from the above simulation results, a good strategic approach to product design is the design of the product and its manufacturing systems are carried out more or less simultaneously, which is called concurrent engineering.

6. Summary and Discussion

Numerous information flows and interactions between development activities characterize the complex and iterative nature of the VDP. In order to reduce lead-time, the VDP has been shifted from a sequential to a concurrent process. The benefits of concurrent engineering are well recognized. Concurrent execution of design activities reduces time delays in information exchange, but increases the managerial complexity of the VDP. Because of the ever-increasing pressure to reduce lead-time, complete overlapping of design activities is often attempted or encouraged, even though critical requirements or technical information are not yet mature. A system dynamics model was developed to understand the transient behavior of parallel, overlap, and sequential processes in the VDP, and to determine the optimal level of overlapping, considering the development lead-time and total number of reworks.

What we have found is that the concurrent execution of design activities is not necessarily a better process, because of the excessive rework that is generated. The simulation results showed that different execution processes should be applied, depending upon the impact of rework. However, the overlapping process does not mean that the downstream design groups should engage only after sufficient upstream design information is accomplished and released. Early involvement should be encouraged, but the danger of early execution of design activities should be clearly understood. The understanding of neighboring design activities reduces the problems in communication, which thus reduce the chance of producing rework.

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