Application of the Design Structure Matrix to Integrated Product Development Process

by

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Abstract

A challenging aspect of managing complex product development process is the ability to account for iterations, which are inherent in the design process. A leading edge approach to account for iterations in development process is Design Structure Matrix (DSM). This thesis presents an application of DSM methodology to the project planning and management phase of an integrated product development process. The thesis starts by introducing the project management and planning phase of Raytheon's integrated product development process. It presents the DSM methodology applied to construct the baseline DSM model including the analysis performed. The thesis then describes the characterizations performed to augment the DSM capability to study the information exchange dynamics. To capture the hierarchical structure of the integrated product development process, the thesis employed a hierarchical DSM analysis tool, Arch. An improved process architecture is thus developed by applying DSM partitioning analysis. Finally, the thesis concludes by presenting the improvements gained and the proposed process for the project management and planning phase.

Thesis Supervisor: Steven Eppinger
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1. Introduction

Product development process is the new frontier for achieving competitive advantage in today's rapidly changing business environment. The product development process itself could serve as a differentiator for the effectiveness of technology firms. This is particularly true for defense contractors that have to derive significant value from their capability in program management and system integration. A novel approach to the product development process is the Design Structure Matrix (DSM). This tool provides critical capability to model the information dynamics of the development process. This thesis presents an application of this powerful tool to Raytheon's integrated product development process project management and planning phase.

The thesis starts with a brief background to the product development process and goes on to discuss the methodology employed to create the baseline DSM model for the project management and planning phase of the integrated product development process. It discusses the analysis performed using DSM partitioning and concludes with a presentation of the improved project planning and management phase of the integrated product development process.

2. The product development process

A typical integrated product development process entails six stages with several layers of hierarchical sub-processes within each phase or stage. Figure 1 presents the typical structure of an integrated product development process.

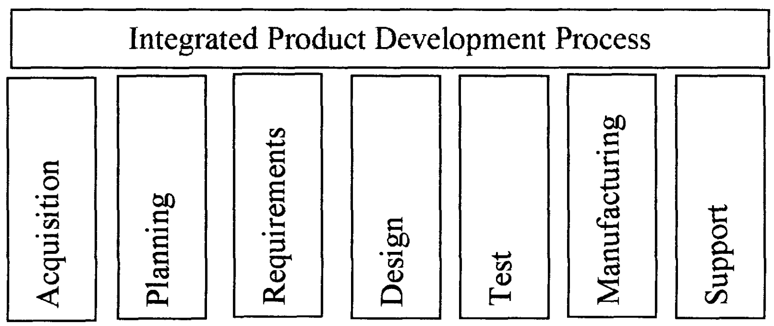

Figure 1 – Integrated product development process

The 'planning stage', also known as the 'program management and planning phase' entails seven sub-processes primarily dealing with the project planning activities and start up gate reviews. This stage is selected for DSM application because it contains a high degree of coupled activities and can thus benefit significantly from DSM applications.

Traditional process improvement approaches cannot deal with coupled activities/iterations since they lack the critical insights required. Eppinger (2001) drew attention to the critical inadequacies of such traditional project management tools. DSM brings an information processing perspective to provide the insights required to address these shortcomings. That is, each individual activity is viewed as an information processing unit that receives inputs from previous tasks and transforms these into suitable information for subsequent tasks downstream. Mapping these dynamics provides the critical insights required to deal with iterations. DSM affords this capability by modeling the information flows rather than the work flows. However, modeling the information exchange is not a trivial task. For example, capturing the planning phase process information exchange dynamics using network diagrams would require several hundreds of pages of block diagrams. DSM facilitates this task too, i.e. by providing a matrix representation that allows efficient modeling of the information dynamics.

3. DSM fundamentals

A Design Structure Matrix (DSM) is a square matrix with identical number of rows and columns. It provides unparalleled utility in capturing large number of interactions and highlighting complex relationships between the activities[1]. DSM is becoming a popular tool for decomposition and analysis of complex processes. Most notably, it has proved its usefulness in system analysis and project management.

One popular type of DSM is an activity-based DSM. An activity-based DSM shows the interactions of each activity in a given process with every other activity in that process. Figure 2 presents an example of an activity-based DSM. In the example the off-diagonal, "X" signifies an information transfer or dependency between activities. Reading across a row reveals all those activities upon which the particular activity represented in that row

[1] There are several types of DSM. Examples include activity-based DSM, parameter-based DSM, component-based DSM and parameter-based DSM. Additional information on DSM can be found at http://cipd.mit.edu and http://www.dsm.org

depends for information; reading down a column reveals all activities to which the particular activity in that column provides information. In general the sub-diagonal marks indicate information feed-forward, while the super-diagonal marks indicate information feedback. Thus, the DSM provides a snapshot of information flow in the process.

		A	B	C	D	E	F	G
Activity	A							X
Activity	B	X		X		X	X	
Activity	C	X						
Activity	D	X					X	
Activity	E		X					
Activity	F	X			X			
Activity	G	X	X	X				

Figure 2 Example DSM

The key to understanding activity-based DSM lies in grasping the concept of iteration and the difference between serial, parallel and coupled activities. In many design processes, much re-work results from poorly sequenced activities where outputs of activities are not available or coordinated in a timely fashion to other activities in the process. Still more re-work stems from highly coupled activities where mutually dependent teams could converge to an acceptable solution only through iteration. The first step towards reducing development time and variation is to minimize or eliminate iterations in the process. This can be achieved by improving the activity sequencing such that the information required by an activity is available when it is time to perform that particular activity. Reordering the rows and columns of the descriptive DSM reveals a prescriptive DSM that minimizes feedback points in the process. Therefore, the goal of DSM partitioning or sequencing becomes an effort to get as many of the interfaces below the diagonal of the DSM as possible. The activity-based DSM techniques are discussed further in sections 4 and 5 of this thesis.

The use of DSM in both research and industrial practice increased greatly in the 1990s. Kusiak and Wang (1993) demonstrate the use of an activity-based DSM to restructure the automobile design process. Browning (1998) applied DSM at Boeing Information, Space and Defense Systems Group to model and analyze cost, schedule and performance for the Uninhabited Combat Air Vehicle program. Still others have applied and expanded the utility of DSM in various industries, including in government projects. Rogers *et al.* (1998) at NASA have developed a web-based DSM tool for system monitoring and controlling multidisciplinary design projects. DSM research is ongoing at various institutions and organizations. Current research includes application of DSM to compare the alignment of the interaction patterns between the product, process and the organization that supports the development process (Eppinger, 2001).

4. Baseline DSM model development and process characterization

Information exchange is the lifeline of complex product development processes. Modeling the information dynamics of the product development process is thus essential for managing the complexity involved. The first task in studying complexity is to decompose the process into sub-processes and activities. However, decomposition requires efficient techniques to capture the dependencies involved. DSM provides this capability by modeling the information dynamics in matrix representation and partitioning.

Construction of the baseline DSM model for the planning stage was performed using a hierarchical DSM simulator. The hierarchical DSM simulator provided the capability required to capture the structure of the integrated product development process. The data and the input/output interdependencies for the planning stage of the integrated product development process were gathered from process experts through Raytheon's integrated product development organization. Data pre-processing was performed to appropriately format the information for the simulator application and some activities were re-labeled for clarity and ease of reporting.

The baseline DSM model depicted the activities, information exchange or flow using an "X" mark. Figure 3 presents the baseline DSM model for the planning phase of the integrated product development process. The model captures the information exchanges including the iterative dependencies. Reading across a row shows the information inputs required to complete the corresponding activity, and reading down the column shows the output information provided by that activity. Understanding and accelerating iterations requires recognition of the iterative information flows and an appreciation of the inherent processes of coupling. Therefore, the input/output (I/O) dynamics were characterized according to the particular temporal role played by information exchange in the execution of a particular activity, as follows:

A) 0 = Needs the input information to start its activity,

B) 1 = Needs the input information to finish its activity,

C) 2 =Requires the input information but the activity could be executed with a derived or assumed parameter.

The baseline DSM model with the I/O characterization is presented in Figure 5. The baseline DSM also captured the first level hierarchy of the planning phase to accurately model the process structure in the integrated product development process. For presentation purposes, the sub-processes or the hierarchical structure is colored in green. The modeling activity could easily be expanded to analyze the development process complexity in various domains.

5. Baseline process analysis

Identifying iterations or feedback points and appropriately planning for their management provides a crucial means for improving quality in product development. Iterations could be accelerated through information technology (faster iteration), coordination of techniques or decreasing the coupling by making fewer feedback loops. Analysis of the baseline DSM model revealed the information exchange points that involve critical iterations or feedback loops. These could be easily identified from the DSM model (presented in Fig. 4) because they lie above the diagonal. The diagonal separates the feed-forward information exchange (below the diagonal) from the feedback information that lies above the diagonal. The feedback points denote that information from the subsequent activity may force a re-work of the preceding activity or may trigger delays. One can also ascertain the sequential, parallel and coupled activities or feedback. Figure 4 presents these observations and the major feedback loops that are the source of inefficiencies and delays in the process.

The baseline model also provides insights on activity dependencies across sub-processes that make hand-off difficult to coordinate. Concurrency is difficult to achieve without significant overhead in task management. Managing the process is complicated because it is difficult to determine activity duration and costs. Consider for example, the Hardware Engineering activity. Since this activity depends on information from various sources, including metrics planning, verification, subcontract/material and data management, it is difficult to estimate its exact duration or cost. This complexity creates difficulty for most mangers to adequately comprehend and plan for the actual efforts and resources required. Concurrent execution without grasping the fundamentals often results in inefficient resource allocation. This effect is clearly demonstrated in the project planning and management phase where full resource loading is required for the entire duration of the planning phase. Figure 5 presents the three activities and their overall duration in the process.

The insights gained from the baseline DSM model are also used to identify the activities that have the most impact on activities downstream. This is achieved by simply reading down the columns of the activities. Accordingly, activities are classified as follows:

A) Group A: activities with output information that feed other activities in more than 5 sub-processes.

B) Group B: activities with output information that feed other activities in more than 2 sub-processes.

C) Group C: activities with output information that feed other activities in less than three sub-processes.

The letters A, B and C are used to denote these group classifications and are presented in Figure 4 in the bottom row of the DSM model.

6. DSM sequencing and improved process design

Improving the project planning phase of the integrated product development process involved application of DSM partitioning algorithm. Partitioning restructures the sequences of activities to formulate a lower triangular form DSM matrix. A lower triangular form provides an optimal architecture for the process since it eliminates and minimizes iterations or feedback points.

While product development is essentially iterative, unplanned iterations cost money and time to market. Iterations occur primarily because of new information from activities upstream or due to the discovery of errors downstream. However, planned iterations could be an important source of quality improvement if managed properly.

DSM methodology affords powerful insights to formulate the sequencing strategy. Consider for example, the dependency of 'logistics support' and 'scope management' activities, labeled "0" and the dependency of 'process tailoring' and 'metrics planning' activities dependency labeled "1". The schematic of the baseline model presented in Figure 6A highlights these feedback points. It becomes evident from studying these input/output dynamics that the dependency assigned a "0" value needs to be below the diagonal and the dependency with "1" needs to be close to the diagonal. This modified strategy can provide the capability needed to execute logistics support without having to wait on 'scope management' activity to complete its work. This speeds the process and also allows 'scope management' to complete its work earlier. 'Metrics planning' and 'process tailoring' are grouped together enabling concurrent execution. This improves coordination and resource efficiency. The results are presented in Figure 6B as part of the improved process architecture.

The insights gained from the grouping strategy based on output information also helped in determining the sequencing approaches. For example, the activity 'gate review' and 'contract baseline' presented in Figure 8 are classified as group A activities with impacts on activities in more than five sub-processes. These activities are therefore, architected to be performed earlier in the process. As the name suggests, the 'gate review' activity represents the check points within the project management and planning process. There is critical improvement to be gained by performing this activity earlier or concurrently with activities in the process. That is, for example, 'Hardware Engineering' under the baseline model has to wait until the 'gate review' activity reaches completion. In the improved process presented in Figure 9, 'Hardware Engineering' could complete its activities earlier since it could independently coordinate its needs. This saves money by speeding up the development process and most importantly, also affords the flexibility for individual activities to exit as soon as they are completely executed.

'Subcontract Material' and 'Systems Engineering' activities are grouped together. It is crucial to start these coupled activities as early as possible because they span the entire project management and planning phase. This also provides flexibility to execute and speed up the 'detail planning' activities. Furthermore, they could be executed concurrently as they tend to interdepend on similar information flows. More importantly, this thesis holds that these activities warrant special attention as they provide additional opportunity for improvement. The critical information they demand is from 'financial' planning activity. Prudent project management thus demands intimate attention to this grouped activity. Figure 10 presents the iteration points that need special attention after these activities were segregated together for concurrent execution.

The proposed improved process contains less iterative dynamics, hence is faster and more reliable. This could also be demonstrated using Browning's 1998 model that presents DSM based methodology for analyzing cost, schedule and performance in complex system product development. Browning's methodology proposes using DSM structure and Monte Carlo simulation to predict the distribution of possible project duration. The application involves assigning estimates to both re-work probabilities due to iteration and re-work impact to each instance where interdependence between activities is identified. In addition, the methodology proposes developing an overlap matrix to capture the amount of overlap between activities. In applying the methodology to analyze and demonstrate the performance of the improved proposed process *vis à vis* the baseline process, the analysis for this thesis identified coupled activities in the improved process[2].

[2] This was done merely to show the 'worst case scenarios' in the improved process and for simulation and parameter estimation convenience. It should be noted that the proposed improvement has eliminated a

The same parameter estimates were subsequently applied for the probability, impact and overlap matrix for both the baseline DSM model and improved DSM model. The activities selected are presented in Figures 12A and 12B which highlight the coupling effects which made them ideal candidates for performance evaluation. For ease of reference, the selected activities and their I/O dynamics DSM models are presented below in Figures 13A and B.

Baseline DSM Activity I/O dynamics	Tag	17	18	20	22	23
Systems Engineering - Process ID 2-5.01	17	■	1	1		1
Hardware Engineering - Process ID 2-5.02	18	0	■			1
Specialty Engineering - Process ID 2-5.04	20	0	0	■		1
Product / System Integration - Process ID 2-5.06	22	0	0		■	0
Verification and Validation - Process ID 2-5.07	23	0	0		0	■

Figure 13A Selected activities from baseline DSM model

Improved Process DSM Activity I/O dynamics	Tag	15	23	24	25	26
Systems Engineering - Process ID 2-5.01	15	.	1	1		1
Hardware Engineering - Process ID 2-5.02	23	X	.	X		
Verification and Validation - Process ID 2-5.07	24	X	X	.	X	
Product / System Integration - Process ID 2-5.06	25	X	X	X	.	
Specialty Engineering - Process ID 2-5.04	26	X	X	X		.

Figure 13B Selected activities from improved DSM model

The next step involved crafting the DSM probability matrix. That is, for each interdependence a probability estimate was devised to assess the likelihood that an iteration caused by completion or revision of an activity will cause a re-work in another

significant number of feedback points. This significant improvement in overall performance can be readily appreciated by selecting activities with no feedback in the improved process and comparing them with the baseline process where they previously exhibited considerable feedback.

activity in the process. Figure 14A and B present the probability estimates applied to characterize the DSM probability matrix. For example, the circled 0.1 estimate in Figure 14A indicates that there is an estimated 10% chance of completion of 'Verification and Validation' planning or that uncoordinated information exchange will cause at least some re-work of 'Hardware Engineering' planning. In general, numbers above the diagonal are estimates of the likelihood or the odds of feedback from one activity to another. The numbers below the diagonal have similar characteristics, but represent the chances of a situation of feed-forward. Hence, if the 'Hardware Engineering' planning activity had to be re-worked there would be a 10% chance that 'Specialty Engineering' planning would also have to be re-worked or iterated.

Baseline DSM Probability Matrix	Tag	17	18	20	22	23
Systems Engineering - Process ID 2-5.01	17		0.10	0.01		0.10
Hardware Engineering - Process ID 2-5.02	18	0.10				0.10
Specialty Engineering - Process ID 2-5.04	20	0.00	0.10			0.05
Product / System Integration - Process ID 2-5.06	22	0.10	0.10			0.20
Verification and Validation - Process ID 2-5.07	23	0.20	0.20		0.20	

Feedback

Figure 14A Baseline Process Probability Matrix for selected activities

Improved Process DSM Probability Matrix	Tag	15	23	24	25	26
Systems Engineering - Process ID 2-5.01	15		0.10	0.10		0.01
Hardware Engineering - Process ID 2-5.02	23	0.10		0.10		
Verification and Validation - Process ID 2-5.07	24	0.20	0.20		0.20	
Product / System Integration - Process ID 2-5.06	25	0.10	0.10	0.20		
Specialty Engineering - Process ID 2-5.04	26	0.00	0.10	0.05		

Figure 14B Improved Process Probability Matrix for selected activities

The extent of re-planning caused or that had to be performed for each probability is also captured using DSM impact structure as presented in Figures 15A and B. For example, an estimated 20% of the planning for 'Hardware Engineering' would have to be re-worked or re-done if the projected 10% likelihood of the iteration caused by the 'Verification and Validation' planning activity were to be realized.

Baseline DSM Impact Matrix	Tag	17	18	20	22	23
Systems Engineering - Process ID 2-5.01	17		0.1	0.0		0.2
Hardware Engineering - Process ID 2-5.02	18	0.2				0.2
Specialty Engineering - Process ID 2-5.04	20	0.0	0.2			0.0
Product / System Integration - Process ID 2-5.06	22	0.2	0.2			0.4
Verification and Validation - Process ID 2-5.07	23	0.1	0.1		0.1	

Figure 15A Baseline Process Impact Matrix for selected activities

Improved Process DSM Impact Matrix	Tag	15	23	24	25	26
Systems Engineering - Process ID 2-5.01	15		0.1	0.2		0.0
Hardware Engineering - Process ID 2-5.02	23	0.2		0.2		
Verification and Validation - Process ID 2-5.07	24	0.1	0.1		0.1	
Product / System Integration - Process ID 2-5.06	25	0.2	0.2	0.4		
Specialty Engineering - Process ID 2-5.04	26	0.0	0.2	0.0		

Figure 15B Improved Process Impact Matrix for selected activities

In addition, it is important to note that this thesis also considered the effects of learning that come with the implementation of improved processes. The assumption made for the purposes of this analysis, is that the probability of re-working will fall by a constant fraction with each iteration[3]. To adequately simulate the dynamic nature of learning this

[3] Although it should be noted that Smith and Eppinger (1997) hold that it is not always readily apparent whether re-work probability would increase or decrease with iterations of a task.

thesis employed Cory's (2001) modified version of Browning's (1998) model[4]. For example, for learning curve (LC) parameter 0.2 and initial iteration probability 0.1, the iteration probability will decay exponentially to zero with increasing iteration, as illustrated in Figure 16.

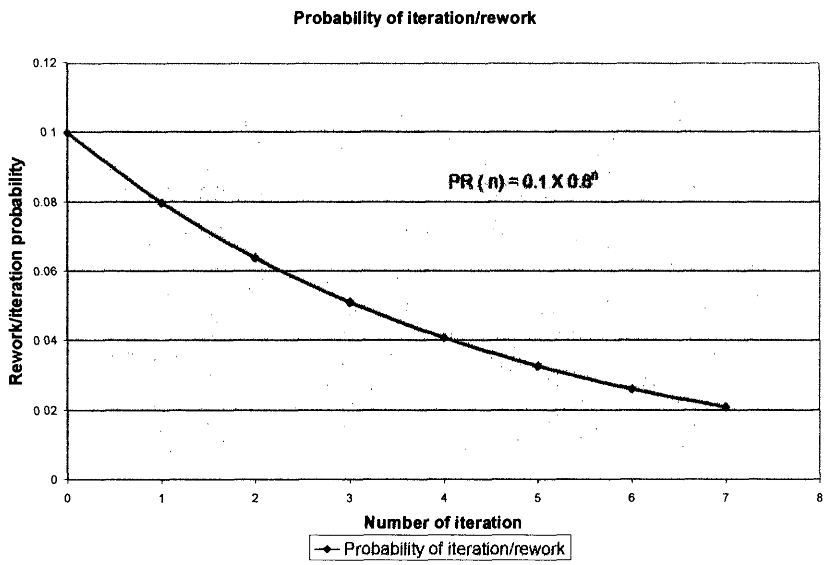

Figure 16 Learning Curve

The learning curve estimates utilized for performance analysis are presented in Figure 19 with the duration parameters simulated. The last step in characterizing the DSM structure for performance analysis involved capturing the amount of overlap between the activities. To simulate the effects of concurrency between the activities, all elements of the DSM structure for the overlap matrix are assigned a zero value. That is, for example, 0% of 'Hardware Engineering' planning must be completed to start planning 'Specialty

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[4] The equation for re-work probability as a function of the number of iteration n:

$P_{i,j}(n) = P_{i,j}(0) * (1 - LC_i)^n$ where $P_{i,j}(0)$ = the estimated probability for the first iteration/re-work

Engineering'. Figures 17A and B present the DSM overlap matrix for the baseline process and the proposed improved process respectively.

Baseline DSM Overlap Matrix	Tag	17	18	20	22	23
Systems Engineering - Process ID 2-5.01	17					
Hardware Engineering - Process ID 2-5.02	18	0.0				
Specialty Engineering - Process ID 2-5.04	20	0.0	0.0			
Product / System Integration - Process ID 2-5.06	22	0.0	0.0			
Verification and Validation - Process ID 2-5.07	23	0.0	0.0		0.0	

Figure 17A Baseline Process Overlap Matrix for selected activities

Improved Process DSM Overlap Matrix	Tag	15	23	24	25	26
Systems Engineering - Process ID 2-5.01	15					
Hardware Engineering - Process ID 2-5.02	23	0.0				
Verification and Validation - Process ID 2-5.07	24	0.0	0.0			
Product / System Integration - Process ID 2-5.06	25	0.0	0.0	0.0		
Specialty Engineering - Process ID 2-5.04	26	0.0	0.0	0.0		

Figure 17B Improved Process Overlap Matrix for selected activities

The amount of impact on the overlapped portion of the activities is assumed to be the same as the impact matrix parameters since the activities completely overlap. Browning (1998) showed that activity durations could be modeled as random variables with triangular distributions. Estimates of the most likely duration value (MLV), best case duration value (BCV), and worst case duration value (WCV) provide the endpoints of this triangular distribution as shown in Figure 18.

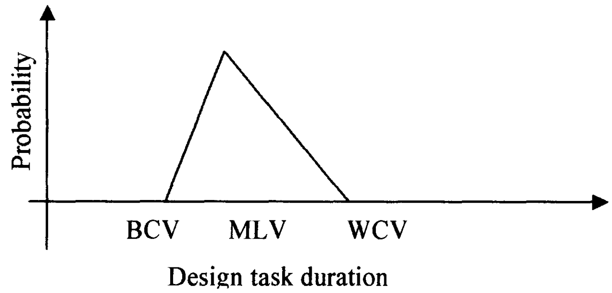

Figure 18 Triangular approximations of task durations

Figure 19 presents the duration and the learning curve parameters applied. The sum of these randomly chosen activity durations will constitute one possible outcome for the total duration for these activities. Numerous repeats will yield the probability distribution function (PDF) for the duration.[5] Accordingly, Mote Carlo simulation[6] was adopted by this thesis, with a view to demonstrating the performance of the selected activity durations in the proposed improved process, in comparison with the baseline process.

Process/activity Name	BCV	MLV	WCV	LC
Systems Engineering - Process ID 2-5.01	7.2	8	9.6	0.6
Hardware Engineering - Process ID 2-5.02	7.2	8	9.6	0.7
Specialty Engineering - Process ID 2-5.04	3.6	4	4.8	0.8
Product / System Integration - Process ID 2-5.06	4.5	5	6	0.6
Verification and Validation - Process ID 2-5.07	5.4	6	7.2	7.5

Figure 19 Duration and learning curve parameters

A total of 1000 simulation runs were performed to compare the distribution of the activities' total durations. As presented in Figures 20 A and B the simulation results

[5] Total process duration can also be shown using cumulative distribution function (CDF).

[6] This thesis employed Soo-Haeng Cho's (2001) Microsoft implementation that drew on much of Browning's work, including application of Latin Hypercube Mote Carlo simulation to capture the skewed right hand shape of the durations.

demonstrated that the proposed improved process has slightly higher duration mean but it produced a lower standard deviation than the baseline process.

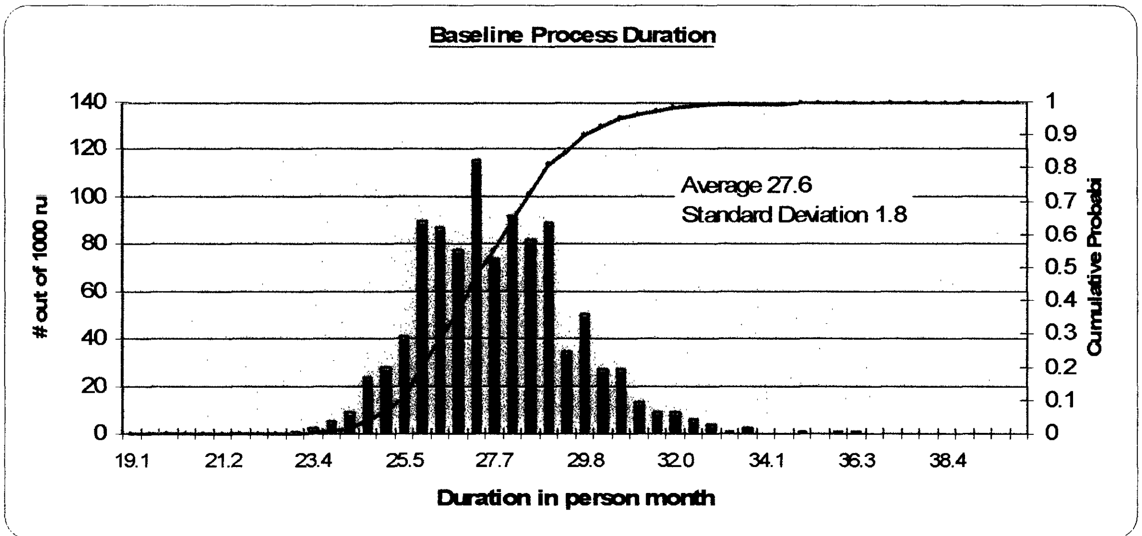

Figure 20A Cumulative distribution function of baseline duration

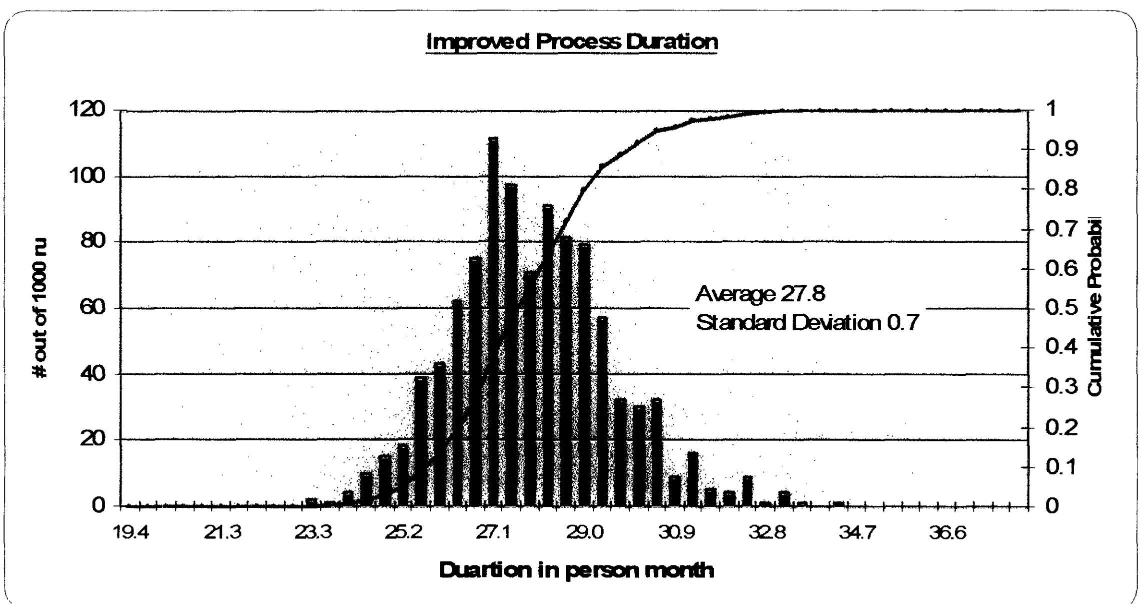

Figure 20B Cumulative distribution function of improved proposed process

Although the improved process has a higher mean it resulted in significant reduction in activity duration variability. It is worth reiterating here that the performance evaluation was done with a select few activities that exhibit feedback characteristics in the improved process. Therefore, it is evident the overall improved process will exhibit a much reduced average duration and variability, given that the improved process delivered significantly reduced feedback loops and iterative/re-work impacts.

7. Conclusions

Process capability is increasingly becoming the key differentiating criterion among competitive technology firms. In the future, it is unlikely that complex system products will compete solely on the basis of technical performance (Browning, 1998). The required amount of sophistication of project planning and control for complex process is/will continue to be unprecedented. For large systems integrators, proficiency in complexity management is both essential and strategic. Balancing all aspects of the development process including price, schedule and performance require efficient analytical tool. This thesis presented DSM methodology and its application for process improvement.

The activity-based DSM applied for the project planning and management phase presented efficient methodology to capture complex interdependencies. It highlighted the feedbacks and potential iterations they can cause. The thesis performed deeper analysis of the interdependencies by classifying the I/O dynamics and the output characteristics of the activities. The insights gained and the partitioned performed rendered an improved process for the project management and planning phase of the integrated product development process. For example, under the current or the baseline process the 'hardware engineering' planning team had to wait for the 'metrics planning' team to define their measurement and analysis strategy for their project. The proposed improved process eliminates this delay in time and the possible iterations because it proposes to execute the 'metrics planning' earlier in the process. This results in the delivery or exchange of the program's measurement and analysis plan to the 'Hardware Engineering' planning activity in a timely fashion. The proposed improved process also eliminates the source of significant iteration/re-work that could materialize from the uncoordinated information exchange between 'Data Management' planning and 'Software Development' planning. Under the proposed improved process, the 'Data Management' planning team defines the critical, often contractual, data exchange format for software code archiving and exchange earlier on in the project planning and management phase, thus enabling the 'Software Development' planning team to plan appropriately for specifications without delay or iteration. Furthermore, the improved process proposes that critical 'Risk and Opportunity (R&O) planning' activity be executed before 'Financial Planning' activity. That is, when the 'Risk and Opportunity planning' team establishes and delivers the methods for classifying and tracking R&O the 'Financial planning' team is able to define the accounting procedures for the R&O without delay or iteration.

Thus, the improved process delivered through the application of DSM techniques saves both money and time. In addition, it addresses a number of typical weaknesses in the current project management and planning process. It eliminated several iterative loops by partitioning the matrix and sequencing the activities. For example, activities within the 'program detail' and planning sub processes could now be executed without any iterative loops. The application identified key control points and efficient coordination structures. The improved process is more robust and allows planners to adjust the process to meet customer expectations.

If appropriately aligned with the organizational structure of the team supporting the project management and planning phase, the optimized process architecture could potentially result in further improvements. Indeed, Eppinger and Salminen (2001) have shown the value of DSM application in three areas of the development process - the organization structure, the product architecture and the process itself.

The findings of this thesis also helped highlight that the contemporary emphasis on concurrent engineering which amounts to increasing parallelism as a solution for process improvement could result in increased coupling and iterations. Research has shown that there is an optimum amount of activity concurrency beyond which additional concurrency becomes detrimental (AitSahlia *et al.*, 1995). Indeed, some models have shown that the goal of process improvement should not be focused on concurrency alone. The objective should be to achieve optimization in all aspects of the development process in order to maximize competitive advantage. Activity-based DSM analyses help determine that optimal point.

8. Analyses

	Process Names	Tag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
ID 2-1	Vision - Processes ID 2-1.01	1	.								X																									X			
	Team building - Process ID 2-1.02	2	X	.			X				X																												
	Program Mang - Process ID 2-1.03	3	X		.		X				X	X						X					X				X		X			X	X	X	X	X			
ID 2-2	Product Break Down -Process ID 2-2.01	4	X			.	X				X																												
	Organization - Process ID 2-2.02	5	X				.	X			X	X														X													
	Work Breakdown - Process ID 2-2.03	6	X				X	.			X																												
	Process Tailoring - Process ID 2-2.04	7	X		X		X		.		X								X																X	X			
ID 2-	Program Overview - Process ID 2-3.01	8	X			X	X	X		.	X																												
	Contract Baseline - Process ID 2-3.02	9									.	X																						X					
ID 2-4	Financial Planning - Process ID 2-4.01	10	X		X		X	X	X		X	.			X											X						X							
	Program Staffing - Process ID 2-4.02	11					X		X			X	.					X																					
	Facilities Plan - Process ID 2-4.03	12	X				X		X		X			.	X	X				X							X	X											
	Capital - Process ID 2-4.04	13							X		X			X	.																								
	IT Resources - Process ID 2-4.05	14							X		X					.																							
	Project Training - Process ID 2-4.06	15									X	X					.																						
	Earn Value Reporting - Process ID 2-4.07	16					X	X	X		X	X						.								X													
ID 2-5	Systems Engineering - Process ID 2-5.01	17				X		X	X		X	X		X		X	X		.	X		X			X	X			X	X		X			X	X			
	Hardware Engineering - Process ID 2-5.02	18				X	X	X	X		X	X	X	X					X	.					X	X				X					X	X			
	Sofware Development - Process ID 2-5.03	19	X			X		X	X		X	X		X					X		.				X	X				X		X		X	X	X			
	Specialty Engineering - Process ID 2-5.04	20				X	X	X	X		X	X							X	X		.			X														
	Logistics Support - Process ID 2-5.05	21				X	X	X	X		X	X		X					X	X		X	.		X									X	X	X			
	Product / System Integration - Process ID 2-5.06	22					X		X		X	X							X	X				.	X											X			
	Verification and Validation - Process ID 2-5.07	23				X	X	X	X		X	X		X					X	X				X	.	X									X	X			
	Subcontract Material - Process ID 2-5.08	24				X	X	X	X		X	X		X					X	X		X			X	.	X					X			X	X			
	Manufacturing Mangement - Process ID 2-5.09	25				X	X	X	X		X	X		X						X					X	X	.			X					X	X			
ID 2-6	Program Security - Process ID 2-6.01	26																										.		X									
	Quality Mangement - Process ID 2-6.02	27				X	X	X	X		X	X								X			X		X		X		.			X			X	X			
	DATA Managemnt - Process ID 2-6.03	28	X				X				X												X			X				.									
	Change Mangement - Process ID 2-6.04	29							X		X															X					.			X					
ID 2-7	Risk and Opportunity -Process ID 2-7.01	30			X				X																					X		.			X				
	Work Product Management - Process ID 2-7.02	31					X				X	X						X	X										X	X		X	.		X				
	Scope Management - Process ID 2-7.03	32			X																											X		.					
	Conduct Gates and Reviews - Process ID 2-7.04	33	X								X								X	X					X		X		X	X			X		.				
	Metrics Planning - Process ID 2-7.05	34	X				X		X		X								X																	.			
	Program Administartion - Process ID 2-7.06	35			X		X																														.		
	Start-Up Readiness Review - Process ID 2-7.07	36									X																								X			.	
	Transition and Closure - Process ID 2-7.08	37									X																								X				.

Figure 3 Baseline DSM model of the project management and planning phase.

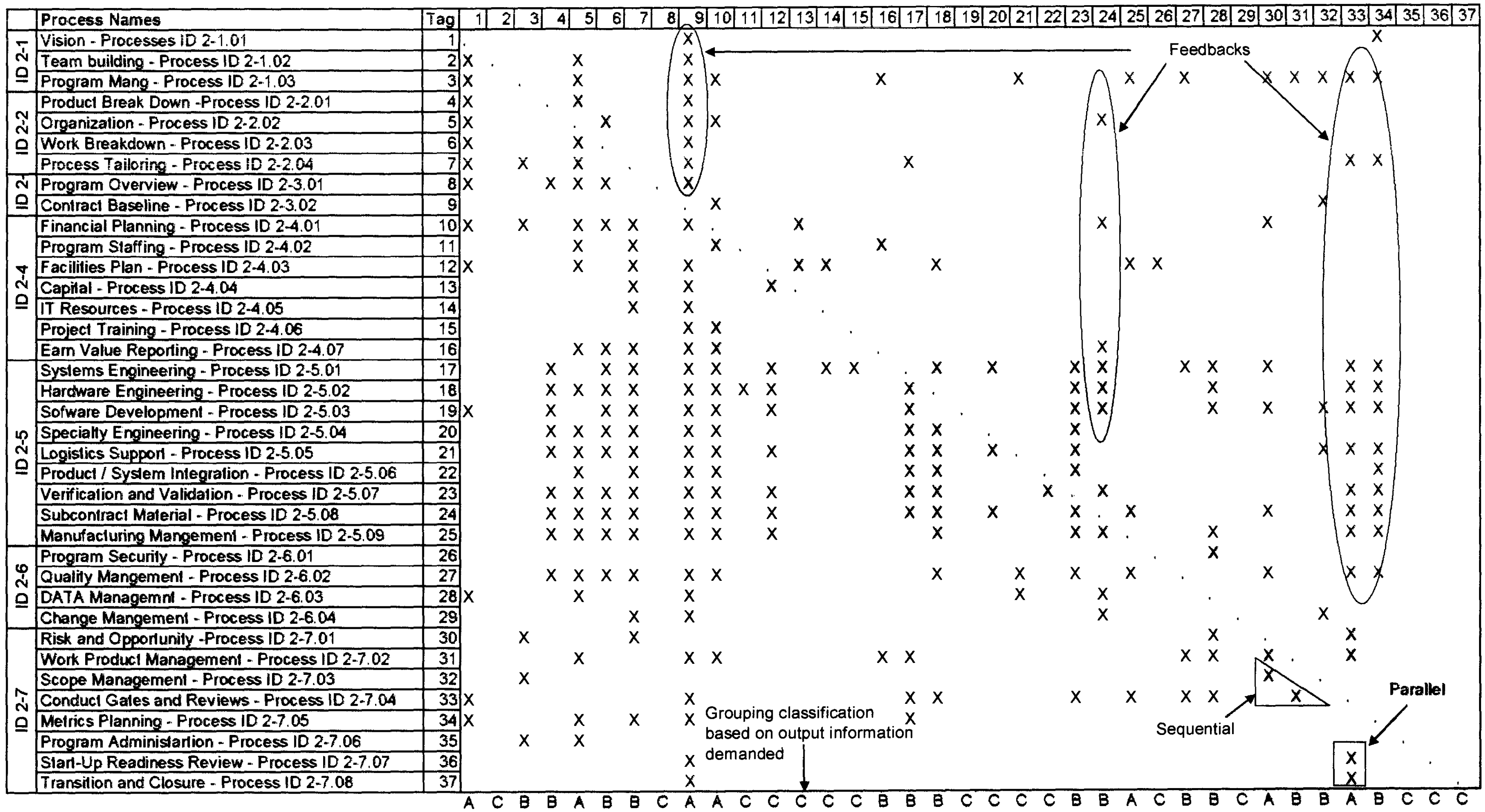

Figure 4 Major feedback loops in the process

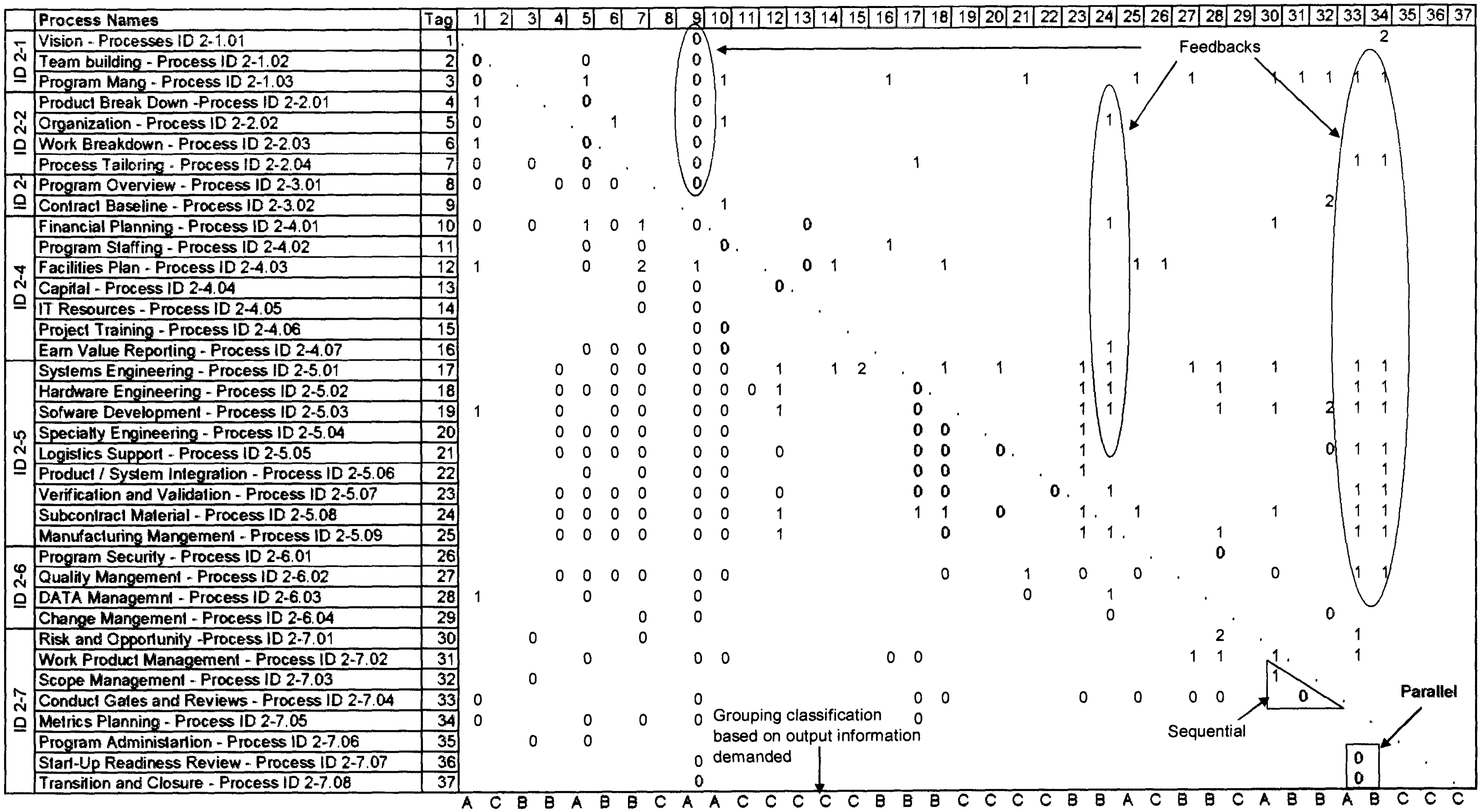

Figure 5 Baseline DSM with input/out dynamics characterized

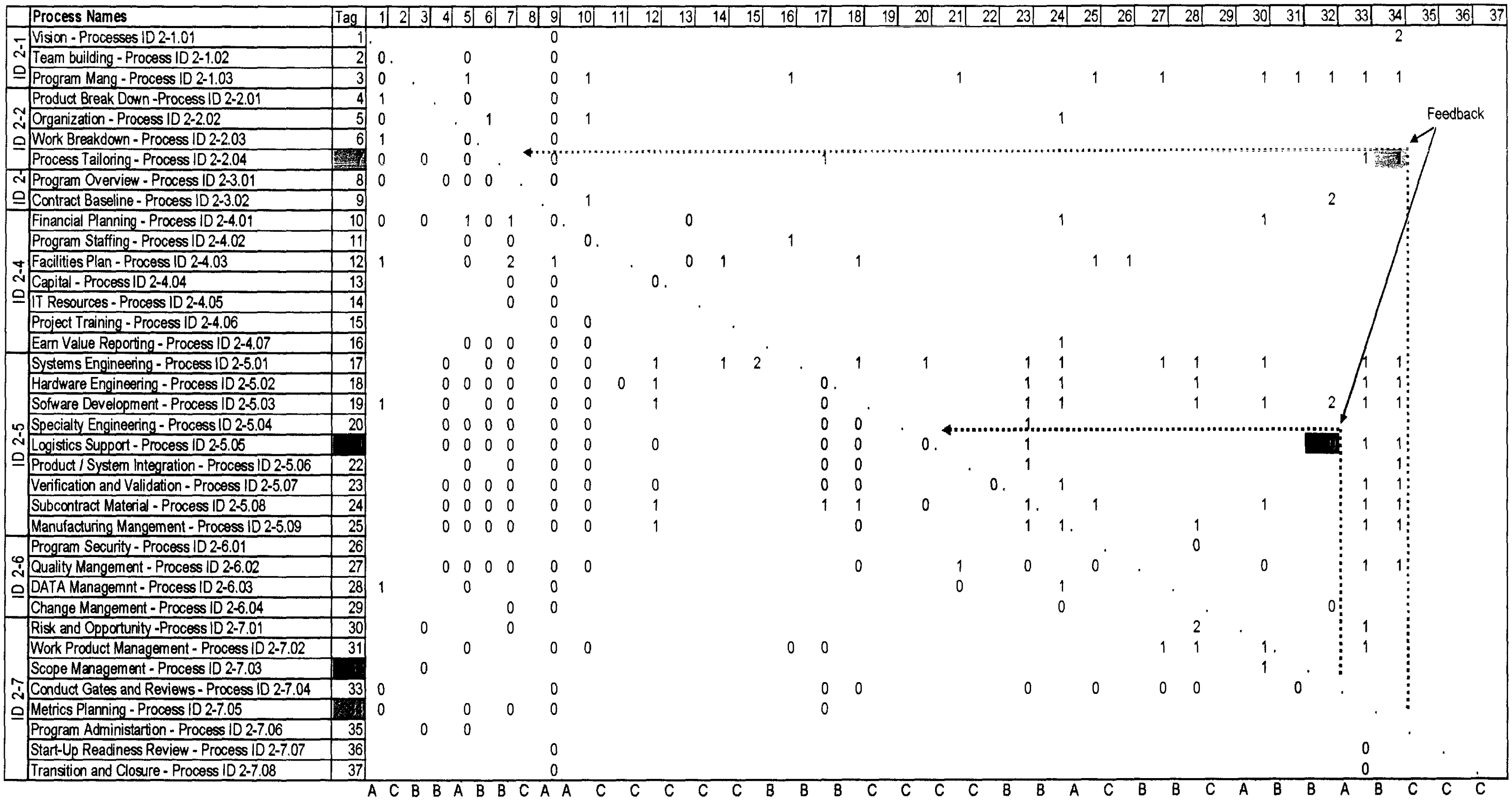

Figure 6A Highlighting the feedback characteristics of the process tailoring activity and the metrics planning in comparison with the scope management and logistics support

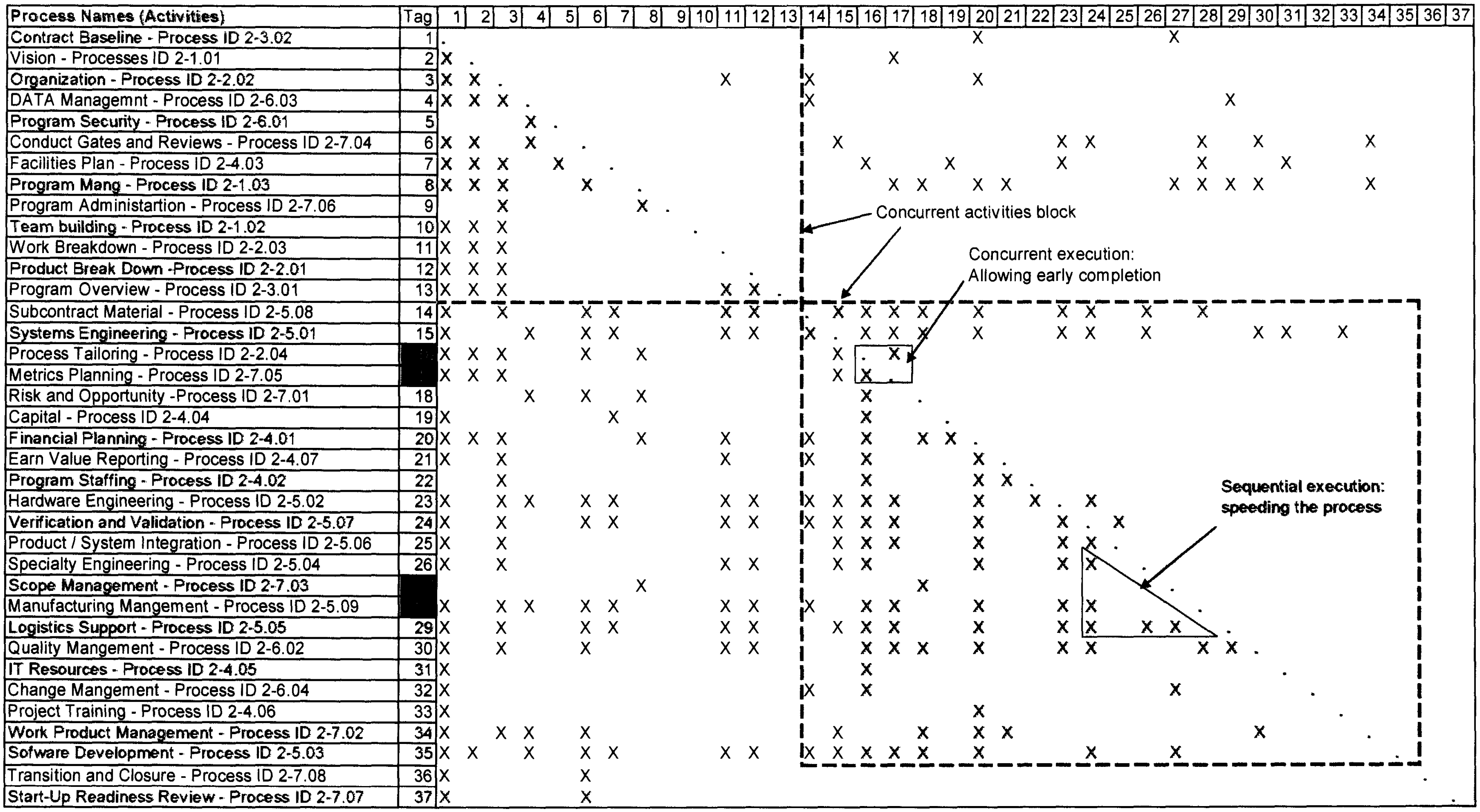

Figure 6B Improved process enabling concurrent execution of process tailoring and metrics planning activity and enabling sequential execution of scope management and logistics support activity

Process Names	Tag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
Contract Baseline - Process ID 2-3.02	1	.																			X							X										
Vision - Processes ID 2-1.01	2	X	.															X																				
Organization - Process ID 2-2.02	3	X	X	.								X			X						X																	
DATA Managemnt - Process ID 2-6.03	4	X	X	X	.										X															X								
Program Security - Process ID 2-6.01	5				X	.																																
Conduct Gates and Reviews - Process ID 2-7.04	6	X	X		X		.									X								X	X				X		X				X			
Facilities Plan - Process ID 2-4.03	7	X	X	X		X		.									X			X				X					X			X						
Program Mang - Process ID 2-1.03	8	X	X	X			X		.									X	X		X	X						X	X	X	X				X			
Program Administartion - Process ID 2-7.06	9			X					X	.																												
Team building - Process ID 2-1.02	10	X	X	X							.																											
Work Breakdown - Process ID 2-2.03	11	X	X	X								.																										
Product Break Down -Process ID 2-2.01	12	X	X	X									.																									
Program Overview - Process ID 2-3.01	13	X	X	X								X	X	.																								
Subcontract Material - Process ID 2-5.08	14	X		X			X	X				X	X		.	X	X	X	X		X			X	X		X		X									
Systems Engineering - Process ID 2-5.01	15	X			X		X	X				X	X		X	.	X	X	X		X			X	X		X				X	X		X				
Process Tailoring - Process ID 2-2.04	16	X	X	X			X		X							X	.	X																				
Metrics Planning - Process ID 2-7.05	17	X	X	X												X	X	.																				
Risk and Opportunity -Process ID 2-7.01	18				X		X		X								X		.																			
Capital - Process ID 2-4.04	19	X						X									X			.																		
Financial Planning - Process ID 2-4.01	20	X	X	X					X			X			X		X		X	X	.																	
Earn Value Reporting - Process ID 2-4.07	21	X		X								X			X		X				X	.																
Program Staffing - Process ID 2-4.02	22			X													X				X	X	.															
Hardware Engineering - Process ID 2-5.02	23	X		X	X		X	X				X	X		X	X	X	X			X		X	.	X													
Verification and Validation - Process ID 2-5.07	24	X		X			X	X				X	X		X	X	X	X			X			X	.	X												
Product / System Integration - Process ID 2-5.06	25	X		X												X	X	X			X			X	X	.												
Specialty Engineering - Process ID 2-5.04	26	X		X								X	X			X	X				X			X	X		.											
Scope Management - Process ID 2-7.03	27								X										X									.										
Manufacturing Mangement - Process ID 2-5.09	28	X		X	X		X	X				X	X		X		X	X			X			X	X				.									
Logistics Support - Process ID 2-5.05	29	X		X			X	X				X	X			X	X	X			X			X	X		X	X		.								
Quality Mangement - Process ID 2-6.02	30	X		X			X					X	X				X	X	X		X			X	X				X	X	.							
IT Resources - Process ID 2-4.05	31	X															X															.						
Change Mangement - Process ID 2-6.04	32	X													X		X											X					.					
Project Training - Process ID 2-4.06	33	X																			X													.				
Work Product Management - Process ID 2-7.02	34	X		X	X		X									X			X		X	X									X				.			
Sofware Development - Process ID 2-5.03	35	X	X		X		X	X				X	X		X	X	X	X	X		X				X			X								.		
Transition and Closure - Process ID 2-7.08	36	X					X																														.	
Start-Up Readiness Review - Process ID 2-7.07	37	X					X																															.

Figure 7 Improved process architected for the project planning and management phase

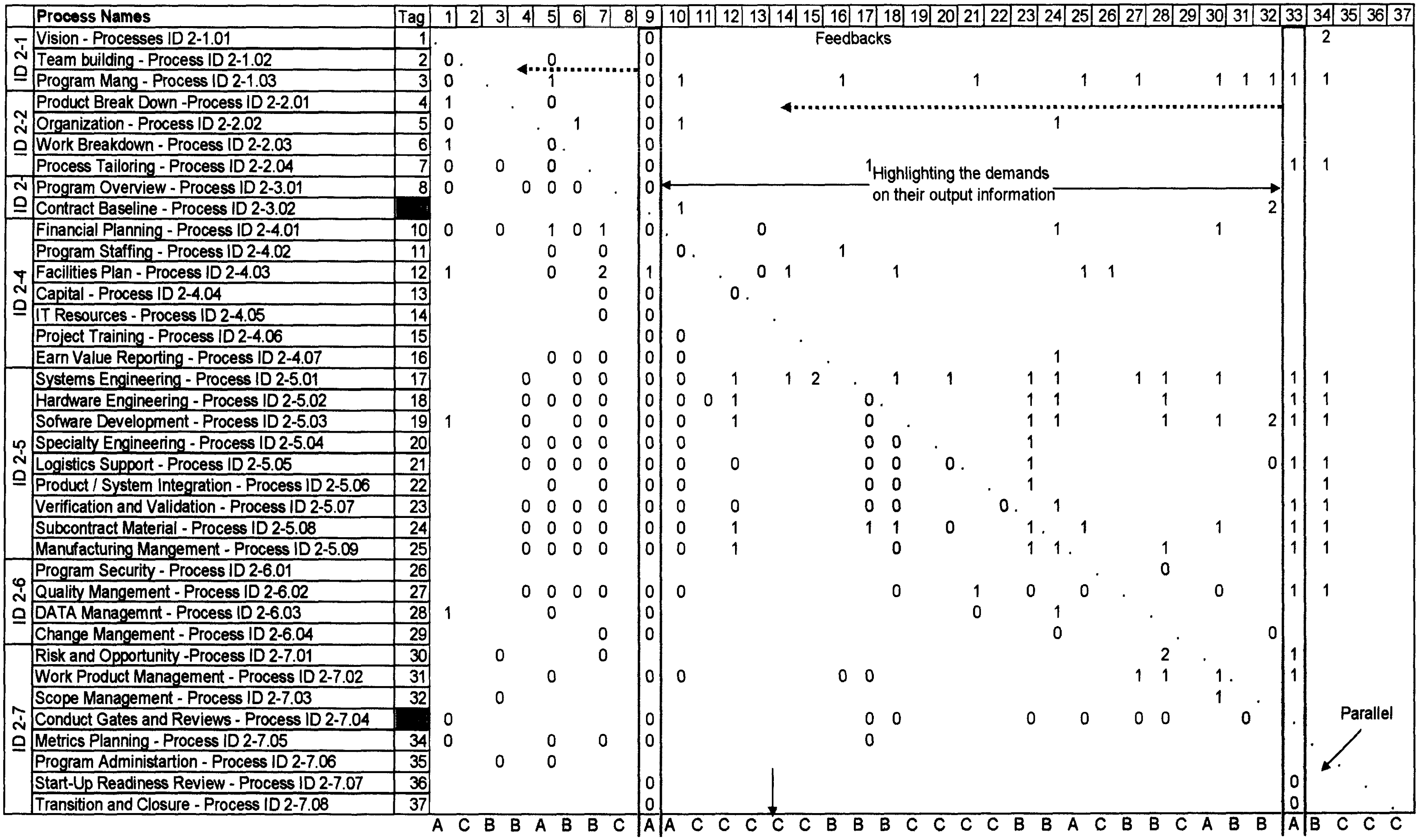

Figure 8 highlighting examples of activities with impacts on activities down stream.

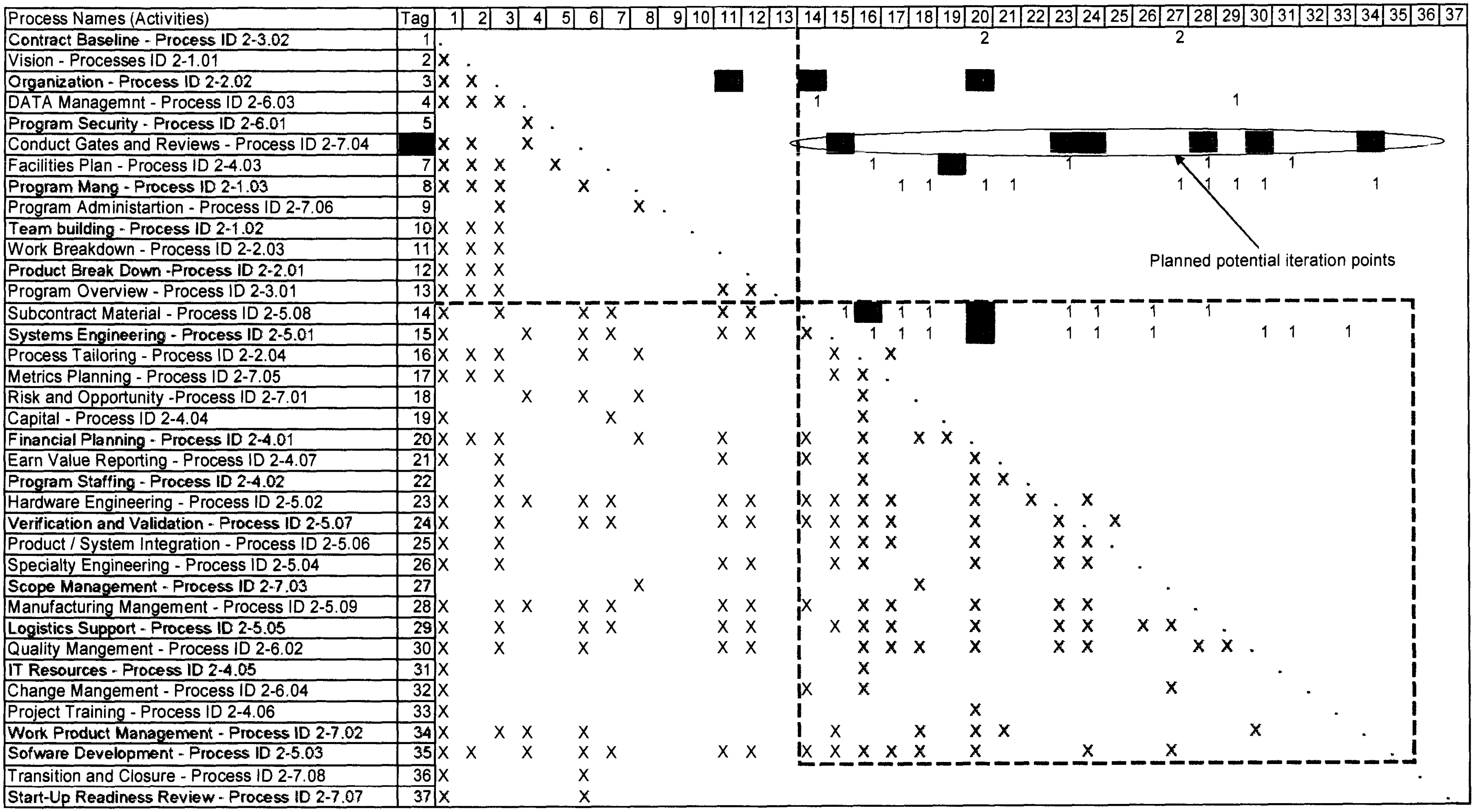

Figure 9 Identified planned iterations and learning points

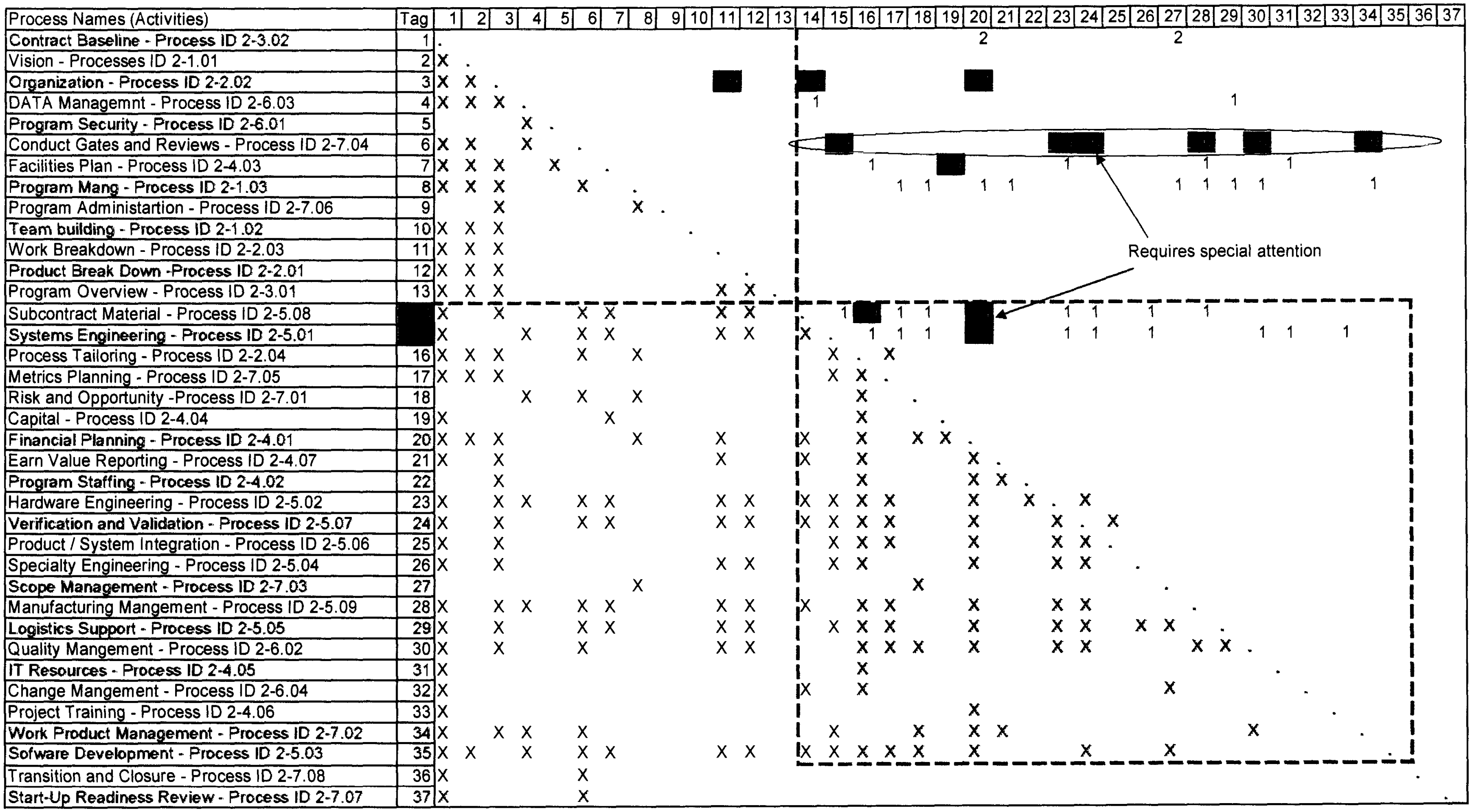

Figure 10 Iterations dynamics that require special attention

Process Names (Activities)	Tag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
Contract Baseline - Process ID 2-3.02	1	.																			2							2										
Vision - Processes ID 2-1.01	2	X	.																																			
Organization - Process ID 2-2.02	3	X	X	.								0			0						0																	
DATA Managemnt - Process ID 2-6.03	4	X	X	X	.										1															1								
Program Security - Process ID 2-6.01	5				X	.																																
Conduct Gates and Reviews - Process ID 2-7.04	6	X	X		X		.									0								0	0				0		0				0			
Facilities Plan - Process ID 2-4.03	7	X	X	X		X		.									1			0				1					1			1						
Program Mang - Process ID 2-1.03	8	X	X	X			X		.									1	1		1	1						1	1	1	1				1			
Program Administartion - Process ID 2-7.06	9			X					X	.																												
Team building - Process ID 2-1.02	10	X	X	X							.																											
Work Breakdown - Process ID 2-2.03	11	X	X	X								.																										
Product Break Down -Process ID 2-2.01	12	X	X	X									.																									
Program Overview - Process ID 2-3.01	13	X	X	X								X	X	.																								
Subcontract Material - Process ID 2-5.08	14	X		X			X	X				X	X		.	1	0	1	1		0			1	1		1		1									
Systems Engineering - Process ID 2-5.01	15	X			X		X	X				X	X		X	.	1	1	1		0			1	1		1				1	1		1				
Process Tailoring - Process ID 2-2.04	16	X	X	X			X		X							X	.	X																				
Metrics Planning - Process ID 2-7.05	17	X	X	X												X	X	.																				
Risk and Opportunity -Process ID 2-7.01	18				X		X		X								X		.																			
Capital - Process ID 2-4.04	19	X						X									X			.																		
Financial Planning - Process ID 2-4.01	20	X	X	X					X			X			X		X		X	X	.																	
Earn Value Reporting - Process ID 2-4.07	21	X		X								X			X		X				X	.																
Program Staffing - Process ID 2-4.02	22			X													X				X	X	.															
Hardware Engineering - Process ID 2-5.02	23	X		X	X		X	X				X	X		X	X	X	X			X		X	.	X													
Verification and Validation - Process ID 2-5.07	24	X		X			X	X				X	X		X	X	X	X			X			X	.	X												
Product / System Integration - Process ID 2-5.06	25	X		X												X	X	X			X			X	X	.												
Specialty Engineering - Process ID 2-5.04	26	X		X								X	X			X	X				X			X	X		.											
Scope Management - Process ID 2-7.03	27								X										X									.										
Manufacturing Mangement - Process ID 2-5.09	28	X		X	X		X	X				X	X		X		X	X			X			X	X				.									
Logistics Support - Process ID 2-5.05	29	X		X			X	X				X	X			X	X	X			X			X	X		X	X		.								
Quality Mangement - Process ID 2-6.02	30	X		X			X					X	X				X	X	X		X			X	X				X	X	.							
IT Resources - Process ID 2-4.05	31	X															X															.						
Change Mangement - Process ID 2-6.04	32	X													X		X											X					.					
Project Training - Process ID 2-4.06	33	X																			X													.				
Work Product Management - Process ID 2-7.02	34	X		X	X		X									X			X		X	X									X				.			
Sofware Development - Process ID 2-5.03	35	X	X		X		X	X				X	X		X	X	X	X	X		X				X			X								.		
Transition and Closure - Process ID 2-7.08	36	X					X																														.	
Start-Up Readiness Review - Process ID 2-7.07	37	X					X																															.

Figure 11 Improved process for the project management and planning phase.

	Process Name	Tag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
ID 2-1	Vision - Processes ID 2-1.01	1	■								0																									2			
	Team building - Process ID 2-1.02	2	0	■			0				0																												
	Program Mang - Process ID 2-1.03	3	0		■		1				0	1						1	1			1	1	1		1	1		1			1	1	1	1	1			
ID 2-2	Product Break Down -Process ID 2-2.01	4	1			■	0				0																												
	Organization - Process ID 2-2.02	5	0				■	1			0	1														1													
	Work Breakdown - Process ID 2-2.03	6	1				0	■			0																												
	Process Tailoring - Process ID 2-2.04	7	0		0	0	0	0	■		0							0	1													1			1	1			
ID 2-	Program Overview - Process ID 2-3.01	8	0			0	0	0		■	0																												
	Contract Baseline - Process ID 2-3.02	9									■	1							1								1		1	1			1	2					
ID 2-4	Financial Planning - Process ID 2-4.01	10	0		0		1	0	1		0	■			0											1						1							
	Program Staffing - Process ID 2-4.02	11					0		0			0	■					1																					
	Facilities Plan - Process ID 2-4.03	12	1				0		2		1			■	0	1				1							1	1											
	Capital - Process ID 2-4.04	13									0			0	■																								
	IT Resources - Process ID 2-4.05	14									0					■																							
	Project Training - Process ID 2-4.06	15									0	0					■																						
	Earn Value Reporting - Process ID 2-4.07	16									0	0						■								1													
ID 2-5	**Systems Engineering - Process ID 2-5.01**	17									0	0		1		1	2		■	1		1			1	1			1	1		1			1	1			
	Hardware Engineering - Process ID 2-5.02	18				0	0	0	0		0	0	0	1					0	■					1	1				1					1	1			
	Sofware Development - Process ID 2-5.03	19	1			0		0	0		0	0		1					0		■				1	1				1		1		2	1	1			
	Specialty Engineering - Process ID 2-5.04	20				0	0	0	0		0	0							0	0		■			1														
	Logistics Support - Process ID 2-5.05	21				0	0	0	0		0	0		0					0	0		0	■		0									0	1	1			
	Product / System Integration - Process ID 2-5.06	22					0		0		0	0							0	0				■	0											1			
	Verification and Validation - Process ID 2-5.07	23				0	0	0	0		0	0		0					0	0				0	■	1									1	1			
	Subcontract Material - Process ID 2-5.08	24				0	0	0	0		0	0		1					1	1		0			1	■	1					1			1	1			
	Manufacturing Mangement - Process ID 2-5.09	25				0	0	0	0		0	0		1						0					1	1	■			1					1	1			
ID 2-6	Program Security - Process ID 2-6.01	26																										■		0									
	Quality Mangement - Process ID 2-6.02	27				0	0	0	0		0	0								0			1		0		0		■			0			1	1			
	DATA Managemnt - Process ID 2-6.03	28	1				0				0												0			1				■									
	Change Mangement - Process ID 2-6.04	29							0		0															0					■			0					
ID 2-7	Risk and Opportunity -Process ID 2-7.01	30			0				0																					2		■			1				
	Work Product Management - Process ID 2-7.02	31					0				0	0						0	0										1	1		1	■		1				
	Scope Management - Process ID 2-7.03	32			0																											1		■					
	Conduct Gates and Reviews - Process ID 2-7.04	33	0								0								0	0					0		0		0	0			0		■				
	Metrics Planning - Process ID 2-7.05	34	0				0		0		0								0																	■			
	Program Administartion - Process ID 2-7.06	35			0		0																														■		
	Start-Up Readiness Review - Process ID 2-7.07	36									0																								0			■	
	Transition and Closure - Process ID 2-7.08	37									0																								0				■
			A	C	B	B	A	B	B	C	A	A	C	C	C	C	C	B	B	B	C	C	C	C	B	B	A	C	B	B	C	A	B	B	A	B	C	C	C

Activities seleceld to demonstrate performance

Figure 12A Baseline DSM model with selected activities for performance analysis.

Process Names (Activities)	Tag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	[redacted]	16	17	18	19	20	21	22	[redacted]	[redacted]	[redacted]	[redacted]	27	28	29	30	31	32	33	34	35	36	37
Contract Baseline - Process ID 2-3.02	1	.																			2							2										
Vision - Processes ID 2-1.01	2	X	.																																			
Organization - Process ID 2-2.02	3	X	X	.								0			0						0																	
DATA Managemnt - Process ID 2-6.03	4	X	X	X	.										1															1								
Program Security - Process ID 2-6.01	5				X	.																																
Conduct Gates and Reviews - Process ID 2-7.04	6	X	X		X		.									0								0	0				0		0				0			
Facilities Plan - Process ID 2-4.03	7	X	X	X		X		.									1			0				1					1			1						
Program Mang - Process ID 2-1.03	8	X	X	X			X		.									1	1		1	1						1	1	1	1				1			
Program Administartion - Process ID 2-7.06	9			X					X	.																												
Team building - Process ID 2-1.02	10	X	X	X							.																											
Work Breakdown - Process ID 2-2.03	11	X	X	X								.																										
Product Break Down -Process ID 2-2.01	12	X	X	X									.																									
Program Overview - Process ID 2-3.01	13	X	X	X								X	X	.																								
Subcontract Material - Process ID 2-5.08	14	X		X			X	X				X	X		.	1	0	1	1		0			1	1		1		1									
[redacted]	15	X			X		X	X				X	X		X	.	1	1	1		0			1	1		1				1	1		1				
Process Tailoring - Process ID 2-2.04	16	X	X	X			X		X							X	.	X																				
Metrics Planning - Process ID 2-7.05	17	X	X	X												X	X	.																				
Risk and Opportunity -Process ID 2-7.01	18				X		X		X								X		.																			
Capital - Process ID 2-4.04	19	X						X									X			.																		
Financial Planning - Process ID 2-4.01	20	X	X	X					X			X			X		X		X	X	.																	
Earn Value Reporting - Process ID 2-4.07	21	X		X								X			X		X				X	.																
Program Staffing - Process ID 2-4.02	22			X													X				X	X	.															
[redacted]	23	X		X	X		X	X				X	X		X	X	X	X			X		X	.	X													
[redacted]	24	X		X			X	X				X	X		X	X	X	X			X			X	.	X												
[redacted]	25	X		X												X	X	X			X			X	X	.												
[redacted]	26	X		X								X	X			X	X				X			X	X		.											
Scope Management - Process ID 2-7.03	27								X										X									.										
Manufacturing Mangement - Process ID 2-5.09	28	X		X	X		X	X				X	X		X		X	X			X			X	X				.									
Logistics Support - Process ID 2-5.05	29	X		X			X	X				X	X			X	X	X			X			X	X		X	X		.								
Quality Mangement - Process ID 2-6.02	30	X		X			X					X	X				X	X	X		X			X	X				X	X	.							
IT Resources - Process ID 2-4.05	31	X															X															.						
Change Mangement - Process ID 2-6.04	32	X													X		X											X					.					
Project Training - Process ID 2-4.06	33	X																			X													.				
Work Product Management - Process ID 2-7.02	34	X		X	X		X									X			X		X	X									X				.			
Sofware Development - Process ID 2-5.03	35	X	X		X		X	X				X	X		X	X	X	X	X		X				X			X								.		
Transition and Closure - Process ID 2-7.08	36	X					X																														.	
Start-Up Readiness Review - Process ID 2-7.07	37	X					X																															.

Figure 12B Improved DSM model with selected activities for performance analysis.

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