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COMPREHENSIVE USE OF A DSM-BASED METHODOLOGY IN AN ACADEMIC SETTING

G. Platanitis, R. Pop-Iliev and A. Barari

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1. Introduction

Often, design engineering educators create their own term design project problems/topics to be assigned to students during a particular course offering within the undergraduate engineering curriculum. Design projects assigned to students in a 1st-year course do not require a large number of tasks to be performed. Few tasks are coupled, and these tasks can be completed fairly quickly. However, 2nd-, 3rd- and 4th-year level design projects are often more complex and multidisciplinary in nature, requiring many tasks with complex relationships to be completed, and often must be performed concurrently. This directly affects the relative difficulty of the design engineering challenge being assigned to students. But can we quantify this level of difficulty in a meaningful way ahead of time so that we can compare and rank different projects in terms of such difficulty? There is a necessity to do so, given the time constraints of an academic term, and the expected student knowledge and skill level for the course in question. With such information, educators can assess the level of difficulty and feasibility (or "doability") of a design project, while students can use the information to efficiently organize tasks and carry out the design while reducing the number of iterations. In this paper, the use of DSM methodologies in this context is examined for a 3rd-year engineering design project assigned at UOIT as an example, and is presented in three parts. First, using an eigenvalue and eigenvector analysis on the WTM, the stability of the design process is determined, the modes of the design process are identified, and the tasks that contribute the greatest amount of work to each mode are determined. Second, a sensitivity analysis is performed to compare the theoretically determined dynamics of the design process to the actual dynamics as experience by the students. Finally, random disturbances of varying degrees and points of occurrence are introduced to the design process and their effect on the design process convergence is analyzed.

2. Background

Research in the last several years has focused on methods that improve the organization of design tasks, as well as to anticipate the effects of design changes in a given product design and development process. In a recent example, Barari and Pop-Iliev (2009) extended a cost due to change model [Prasad 2006] to understand the role of rigidity and level of changeability of a design; that is, the total cost or difficulty of a desired change on a design project.

Over the past several years, matrix methodologies have been developed to organize tasks and define relationships between them. Of significance is the Design Structure Matrix (DSM), which is used to define the sequence of and the technical relationships between design tasks. Using this technical structure, strategies have been developed to determine alternative sequences of tasks or task definitions to improve the design process by reducing the number of iterations required [Eppinger et al. 1994]. The Design Structure Matrix (DSM) has been further extended to make use of the fully coupled portion, called the Work Transformation Matrix (WTM) [Smith and Eppinger 1997], which also includes the strengths of task dependencies in terms of the probability of rework of a task when new or modified information is available, such as where the design has not yet satisfied the required specifications. Further, using an eigenstructure analysis, design modes were identified for a camera design and an automobile brake system design. The design modes determine the controlling features of the design iteration. The DSM was further used by Smith and Eppinger (1997) to predict the expected duration of the iterative process, and used optimizing algorithms and the reward Markov chain method to find the best order for coupled design tasks.

Design Structure Matrix methods have been useful in determining sensitivities to design process changes. Cronemyr et al (2001) predicted the effect of improvements to certain aspects of the development process using the simulated to-be/as-is ratio (STAR), which measures sensitivity of the total process time with suggested improvement versus the original process time. In another application of DSM and WTM methods, the design process was represented as a discrete time state-space system, using well established methods of dynamic analysis techniques to investigate and predict the dynamics of the concurrent design process [Kim 2001]. Using a camera design example [Smith and Eppinger 1997], the author was able to predict the required number of iterations for each of the design tasks, proving that for a given task dependency, the required number of iterations is dependent on the eigenvalues of the WTM. This methodology took advantage of modal analysis to determine the stability of each of the design iteration modes.This methodology also overcame deficiencies of previous methods performing stability analysis which used continuous time state-space models [Ong et al. 2003]. Further research in DSM methods includes closed-loop control for the design process [Lee et al. 2004].The authors identified the tasks consuming large, disproportionate amounts of resources and time to complete. They then determined a closed-loop gain matrix based on eigenvalue analysis, defined to improve the stability and convergence rate of design tasks, as well as to guide resource distribution to expedite particularly slow tasks.

This paper presents a comprehensive use of DSM methodologies in an academic setting, with a third-year engineering design project as a case study. The design process is analyzed to determine convergence characteristics based on the eigenvalues of the system, followed by a sensitivity analysis on the originally determined DSM matrix based on data provided by students in terms of task durations and number of iterations for each task. Finally an investigation of the design process convergence due to unexpected events, or random disturbances, is performed.

3. Method Implementation Example

Engineering students enrolled in mechanical-based programs at UOIT in their third year undertake an integrated design project between two courses which combines concepts of CAD/CAM/CAE design principles (3D Scanning, Solid Modelling, Rapid Prototyping, Finite Element Methods, etc.) with kinematic and dynamic analysis of machines. Working in groups of about 4-5, students were charged with designing a mechanism for handling and manipulating three different tire sizes, to be picked up from three input conveyor belts, and placed on an output conveyor (see Fig. 1). The mechanism must be designed with a factor of safety between 2.5 and 5, and it must be able to handle tires of a maximum weight of 50 kg. Students demonstrated their design via a scaled-down prototype using Lego Mindstorms®, but were required to design the manipulator in CAD using real parts and to the proper size. A suggested task list and order thereof is given below, though many of the tasks will be coupled to some degree. Also included are the best and worst case task duration times (in hrs) per iteration given for the coupled tasks, C-L, as determined from the student data (see Sec. 5) in Table 1:

Table 1. Task Duration Times (best and worst case) for Tire and Wheel Manipulator Design Process

Tasks	Duration/Iteration Step (hrs.), Best & Worst Case	Tasks	Duration/Iteration Step (hrs.), Best & Worst Case
A. Determine specifications		G. Finite Element Analysis	6, 10
			1.5, 10
B. Design concept	4, 10	H. Dynamic simulation	1, 15

C. Design arm	2, 10	I. Factor of safety	1, 4
D. Design arm joints	5, 10	J. Failure mode analysis	27, 40
E. Design grip mechanism	4.5, 5	K. Build prototype	2, 5
F. Design rotating base		L. Evaluate prototype	

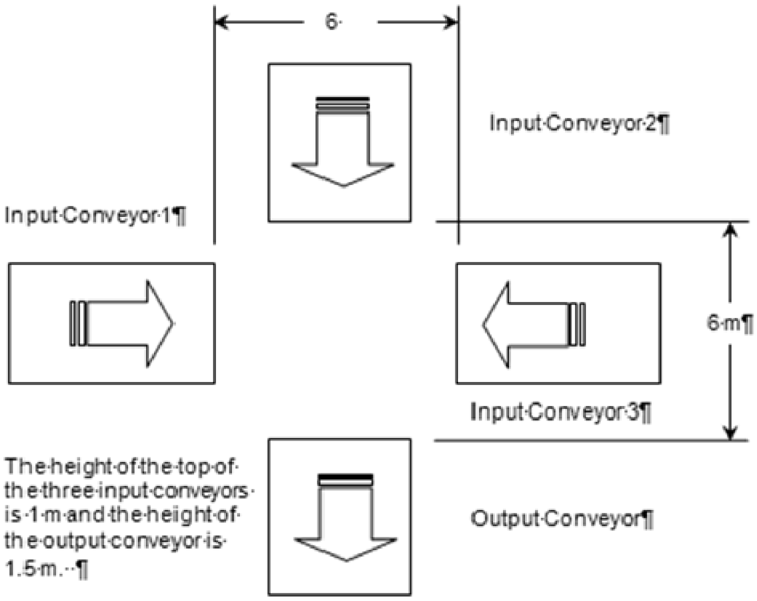

Figure 1. Conveyor belt layout and scaling pertaining to tire manipulator design project

	A	B	C	D	E	F	G	H	I	J	K	L
A												
B	X											
C		X		X	X	X	X		X	X	X	X
D			X		X	X	X		X	X	X	X
E			X	X			X		X	X	X	X
F		X	X	X	X				X		X	X
G		X	X	X	X	X			X	X		X
H		X	X	X	X	X	X		X	X		X
I			X	X	X	X	X	X		X		X
J			X	X	X	X	X	X	X			
K		X	X	X	X	X	X	X	X	X		X
L			X	X	X	X	X	X	X	X	X	

X – dependency of one task on another

	A	B	C	D	E	F	G	H	I	J	K	L
A												
B	S											
C		S		S	W	W	W		W	W	W	W
D			M		W	W	W		W	S	W	W
E			M	W			M		W	S	W	W
F		W	W	W	W				W		W	W
G		W	W	W	W	W			S	W		W
H		W	M	M	M	M	W		W	W		W
I			W	W	W	W	S	W		W		W
J			W	W	W	W	M	W	M			W
K		M	W	W	W	W	W	M	W	W		W
L			W	W	W	W	W	W	W	W	S	

S – strong dependency between tasks W – weak dependency between tasks
M – medium dependency between tasks

Figure 2. DSM (left) and WTM (right) matrix representation for tasks to be performed in tire manipulator design

3.1 Design Structure Matrix (DSM)

The tasks for the tire manipulator design process were then organized into a matrix structure (DSM), representing the relationships between all the tasks (Fig. 2). The tasks are listed down the left side and along the top, in some logical 'order' that they are to be completed (if there was no coupling between tasks). In this representation, a character 'X' is placed in the off-diagonal boxes to show the dependency of a task with another. For example, an 'X' in box I-F (row I, column F) means that Task I is dependent on information from the completion of Task F. Ideally, one would prefer to have dependencies indicated in only the lower triangle, indicating a feedforward direction of task dependencies. Unfortunately, complex projects will have some amount of feedback involved between downstream and upstream tasks, meaning that upstream tasks will have some amount of rework.

3.2 Work Transformation Matrix

A further extension of the DSM is the Work Transformation Matrix (WTM), which shows the strength of the dependencies between tasks [Cronemyr et al (2001), Eppinger et al (1994), Kim (2001), Smith and Eppinger (1997)[1,2]]. Several assumptions need to be made to perform the stability analysis on the design process [Smith and Eppinger 1997[1]]:

- All tasks are completed at every stage (fully parallel iteration).
- Rework is a function of work done in the previous iteration stage.
- Work transformation parameters are time invariant.

For this study, the strength of the dependencies will be simple [Smith and Eppinger 1997[1]], and assigned the following numerical values: 0.5, 0.25, and 0.05 for strong (S), medium (M), and weak (W) dependencies respectively. Alternatively, dependence information can be defined as [Eppinger et al. 1994]:

- Strong – information required from previous task to begin task.
- Medium – information required to end task.
- Weak – information required to check result compatibility.
- Zero – no information required.

This dependency strength can be looked at as the amount of work (in terms of a percentage of time to determine a parameter) that the upstream task creates for the dependent downstream task. For the tire manipulator, the WTM is shown in Fig. 2 (right). Using the numerical version of the coupled block of the WTM (Tasks C to L), the eigenvalues and eigenvectors will be determined. From this information, the task that will contribute the greatest amount of work will be determined.

3.3 Mathematical Formulation

At each iteration stage, work will have been completed for each task. The idea of the work vector is introduced here, and the elements of the work vector (each associated with a task) indicate how much work is left for each task to complete. Initially, the work vector is a column vector of ones (all of the work remains for each task). As the design process progresses from iteration stage t, the work remaining at the next stage is given by [Kim (2001), Smith and Eppinger (1997[1])]:

$$\mathbf{u}_{t+1} = \mathbf{A}\mathbf{u}_t \tag{1}$$

where $\mathbf{u}_t$ is the work vector at stage t and **A** contains the strength dependencies of the WTM. Each a_{ij} element ($i \neq j$) implies that doing a unit of work on task j creates a_{ij} units of work on task i. From the initial work vector $\mathbf{u}_0$, the remaining work at stage t may alternatively be given by:

$$\mathbf{u}_t = \mathbf{A}^t\mathbf{u}_0 \tag{2}$$

Summing up all the work vectors after M iterations gives the total work vector for the entire design process:

$$\mathbf{u}_{tot} = \sum_{t=0}^{M}\mathbf{u}_t = \sum_{t=0}^{M}\mathbf{A}^t\mathbf{u}_0 = \left(\sum_{t=0}^{M}\mathbf{A}^t\right)\mathbf{u}_0 \tag{3}$$

Treating the dynamics of the design process as a discrete-time system is logical [Kim 2001], noting that the work vector is computed at discrete intervals (the iteration stages themselves). The dynamics of the 'discrete' system represented by Eq. 1 can be analyzed as a continuous time system being sampled at intervals of 1 (i.e., iterations take place at step 1, 2, 3, etc.). To determine the stability of the iterative design process, one can look at the eigenstructure of **A**. If **A** has linearly independent eigenvectors, then **A** can be decomposed as:

$$\mathbf{A} = S \Lambda S^{-1} \quad (4)$$

where Λ is a diagonal matrix containing the eigenvalues of **A** and S is the eigenvector matrix. A discrete time system is stable if the magnitude of its eigenvalues lie within the unit circle on a complex plane [Kim 2001]. It is important to note that a stable design process will converge to a technically feasible solution given the specifications of the product to be designed.

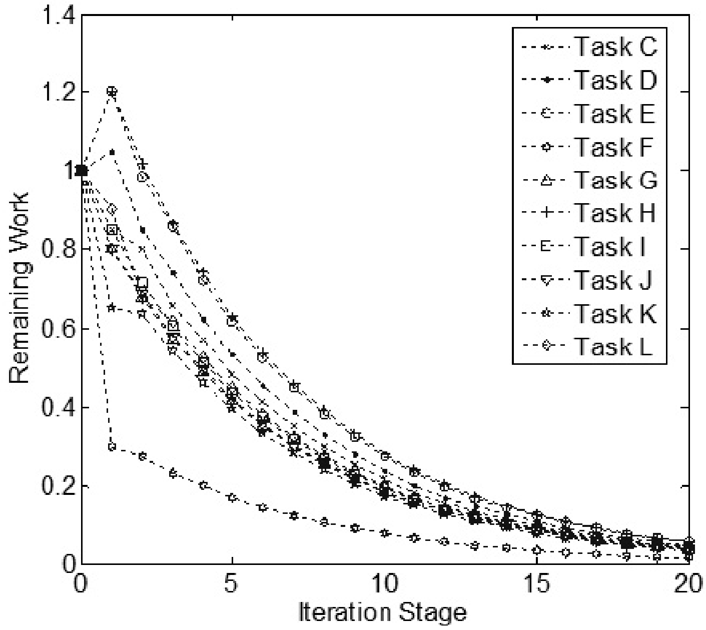

Figure 3. Dynamic response of tire and wheel manipulator design process, showing remaining work for each task at each iteration stage

4. Results of the Stability Analysis

For the WTM of Fig. 2, the eigenvalues and eigenvectors were computed. Also, the remaining work for each task at each iteration stage was computed and plotted in Fig. 3. The dynamic response shows that the design process for the tire manipulator is stable, with a feasible design reached after approximately 15-20 iterations. At this stage, ≤10 percent work remains for each task, at which point only minor product modifications remain after all major iterations have been completed [Lee et al. 2004, Cronemyr et al. 2001]. It is also significant to note that Tasks D, E, and H (design of the arm joints, grip, and dynamic simulation, respectively) show that more work than when the design process originally started remains after the first iteration; however, the work remaining otherwise decreases (monotonically) thereafter, a sufficient condition for stability of the design process [Kim 2001].

4.1 Design Modes

An examination of the eigenvalues of the WTM reveals that there are 8 design modes (see Table 2), six of which are associated with real eigenvalues, and two with complex conjugate eigenvalues, all with a magnitude of < 1. Therefore, each design mode is stable. The modes are ranked based on the magnitude of the eigenvalues. The first mode has the largest magnitude eigenvalue, and will have the slowest dynamics [Kim 2001, Smith and Eppinger 1997[1]]. This mode will have an eigenvector that is strictly positive [Smith and Eppinger 1997[1]], and will be the most obvious to interpret.

Table 2. Eigenvalues for WTM Model of Tire and Wheel Manipulator

Mode	Eigenvalue	Eigenvalue Magnitude
1	0.8512	0.8512
2	-0.5029	0.5029

3	-0.3440	0.3440
4	0.2571	0.2571
5	-0.0626 ± 0.1967i	0.2064
6	-0.1568	0.1568
7	0.0350 ± 0.0304i	0.0464
8	-0.0496	0.0496

According to the Perron-Frobenius Theorem, the largest magnitude eigenvalue of **A** (a non-negative matrix) will be strictly positive and will have a strictly positive eigenvector (the only positive eigenvector) associated with it [Smith and Eppinger 1997[1]]. Table 3 shows the eigenvectors of the two modes with the largest eigenvalues as per Table 2, along with the total work performed on each task.

By examining the elements of the eigenvector associated with the first mode, it can be seen that the tasks which require the greatest amount of work until a feasible solution is reached are associated with the largest values of the eigenvector (Tasks C-E, G, H, J, and L). The dynamic response of the design process reveals that Task D, E, and H require more rework after one iteration, and confirmation of this result is in the fact that these tasks are most significant in the first mode (largest associated eigenvector values). This is indicative of the tighter coupling between these three tasks, as well as being among the most difficult tasks to complete. Summing the work vectors of the design process also indicates that Task D, E, and H require the most work to be done overall.

Table 3. Eigenvectors for Mode 1 and 2, and Total Work Performed for each Task

Design Task	Mode 1	Mode 2	Total Work
C	0.3248	-0.0016	6.8804
D	0.3584	-0.0150	7.5797
E	0.4137	0.2745	8.5905
F	0.1148	-0.0914	3.0704
G	0.2777	-0.6784	6.1058
H	0.4236	-0.0784	8.7406
I	0.2934	0.6692	6.3960
J	0.2815	-0.0008	6.1618
K	0.2633	0.0268	5.7197
L	0.3008	-0.0344	6.5021

An examination of the second mode shows that by far, the dominating task is Task I (evaluating Factors of Safety). Although the eigenvector value for Task I is somewhat significant in the first mode, it is much more significant in the second mode (about twice as much); as such, the task can be considered part of a separate design mode. From the information given by the first and second mode, it can be said that there are two subprocesses – Design and Validation (Mode 1) and Safety Considerations (Mode 2).

The information provided by the eigenstructure analysis above would be primarily useful to instructors as a means of quantifying the relative difficulty of design term projects as well as to students in planning out design tasks for the project. For example, the task of evaluating the design using dynamic simulation (Task H) requires much work in the early stages of iteration (over 100% work remaining), but students can reduce the work involved at this stage (eg., require fewer simulations) by developing the improved concept early in the design process, thus reducing iterations later.

Table 4. Eigenstructures of Original WTM Model and Three Alternative Models

Tasks	Original WTM Mode 1	Original WTM Mode 2	Alt. 1 Mode 1	Alt. 1 Mode 2	Alt. 2 Mode 1	Alt. 2 Mode 2	Alt. 3 Mode 1	Alt. 3 Mode 2	Alt. 3 Mode 3
C	0.3248	0.0016	0.3297	-0.0065	-0.327	0.0082	-0.2315	-0.7018	0.0804
D	0.3584	0.015	0.3572	-0.0101	-0.3517	0.0079	-0.1798	0.4482	0.0166
E	0.4137	0.2745	0.4127	0.28	-0.4043	-0.2809	-0.1961	0.4502	-0.1289
F	0.1148	-0.0914	0.1174	-0.092	-0.1236	0.0913	-0.1046	-0.0254	0.19
F2							-0.4674	-0.1455	0.5291
F3							-0.6117	-0.234	-0.1772
G	0.2777	-0.6784	0.2748	-0.678	-0.2693	0.6769	-0.0807	-0.0095	0.1456
H	0.4236	-0.0784	0.4323	-0.0804	-0.4171	0.0813	-0.3171	-0.1066	-0.065
I	0.2934	0.6692	0.2794	0.667	-0.2847	-0.6676	-0.1715	0.0195	-0.2307
J	0.2815	-0.0008	0.2649	-0.0036	-0.2563	0.0046			
J2					-0.1755	0.0071			
K	0.2633	0.0268	0.2701	0.028	-0.2675	-0.0288	-0.229	0.0658	0.2565
L	0.3008	-0.0344	0.3098	-0.0355	-0.3082	0.0357	-0.2883	-0.1055	-0.6962
Eigenvalues	0.8512	-0.5029	0.8344	-0.5107	0.8573	-0.503	0.6195	-0.3474	-0.1848

F2 = Consider Stability Criteria; J2 = Add Valuable Features

F3 = Design Robot in CAD; (grey) – not among tasks for given WTM matrix.

5. Model Sensitivity Analysis

In order to examine alternate possibilities of DSM-WTM models and their sensitivity to the dynamic response of the design process, the students of the third-year Computer-Aided Design course were assigned to re-examine the DSM-WTM matrix initially proposed. They were required to determine alternative DSM-WTM matrices (defining any additional tasks as necessary), re-examine the task dependencies and/or task order, note the actual number of iterations and number of hours required for each task based on their experience, and predict the total duration of the design project, and include this information in their logbooks. These results were then compared to the predictive model. From this analysis, the sensitivity to the model based on the eigenstructure analysis, actual task iterations, and rework predictions was determined. Table 4 compares the eigenstructures of the alternative matrices (best quality ones) as determined by the students. Groups in general maintained most of the listed tasks from the original WTM matrix, but some determined additional tasks for consideration.

Table 5. Total Work Performed on Each Task Throughout Design Process for each WTM Model

Tasks	Original WTM. Total Work	Alt. 1 Total Work	Alt. 2 Total Work	Alt. 3 Total Work
C	6.8804	6.3921	7.4109	3.0112
D	7.5797	6.9463	7.9917	2.5094
E	8.5905	7.8682	9.028	2.7395
F	3.0704	2.907	3.4221	1.8562
F2				5.186
F3				6.3595
G	6.1058	5.5877	6.3317	1.6723
H	8.7406	8.133	9.2119	3.7792
I	6.396	5.6552	6.6373	2.6975
J	6.1618	5.4031	6.0607	
J2			4.4441	
K	5.7197	5.3558	6.1869	2.8356
L	6.5021	6.0992	7.0785	3.331

(grey) – not among tasks for given WTM matrix

It is worthy of note that the Mode 1 eigenvectors of the second and third alternative WTM matrices contain all real, negative values (opposite of the result of the original and first alternative WTM matrix). We can adopt a similar analysis as that presented in Sec. 4 if we consider just the magnitude of the eigenvector terms (and for consistency, the negative terms in all subsequent modes). From the eigenstructure analysis, it can be seen that the first and second alternative matrices reveal the same modes for the design process as the original WTM matrix (Design and Validation, and Safety Considerations), with common eigenvector terms highlighted for ease of comparison. However, the third alternative as shown reveals a different possible grouping of the tasks in the design process. In this case, the arm design of the manipulator is most dominant in the second mode, with a third mode considering factors of safety and prototype evaluations. In such a case, it may be possible to verify factors of safety determined through the CAD model (via Finite Element Modelling) via a fully working, life-sized prototype operating under a controlled environment.

Table 5 shows the total work done on each task over the duration of the design project for each WTM model, with values highlighted to show which tasks contributed the most work. The original WTM and the first two alternatives show somewhat similar results in terms of the total work done for each task. The third alternative WTM model showed some very different results for total work done on each task. For example, the original WTM model predicted a total work of 6.8804 for Task C (Design Arm), while the third alternative showed a total work of 3.0112. Using the total work vectors computed for each WTM matrix, the total duration of the design project was computed based on estimated task duration times from the various student groups. A diagonal matrix **W** is defined with the diagonal terms containing the task duration times. The following relationship was applied:

$$\text{Total design duration} = \sum_i (\mathbf{WU})_i = \sum_i \left(\mathbf{W} \sum_1^n \mathbf{u}_t \right)_i \qquad (5)$$

where **U** is the vector whose elements are the total work performed for each task in fractional terms. The total duration of the design process was then divided over an eleven week period that the design project took place and then divided by the number of members in each design group. The result was a design project duration between 180 to 776 hours (or 3 to 12 hours per person per week) and can be attributed to factors such as different skill levels and abilities of students, as well as experience and familiarity in the various elements of the design project. Student groups also found that their actual project duration lay within the above range.

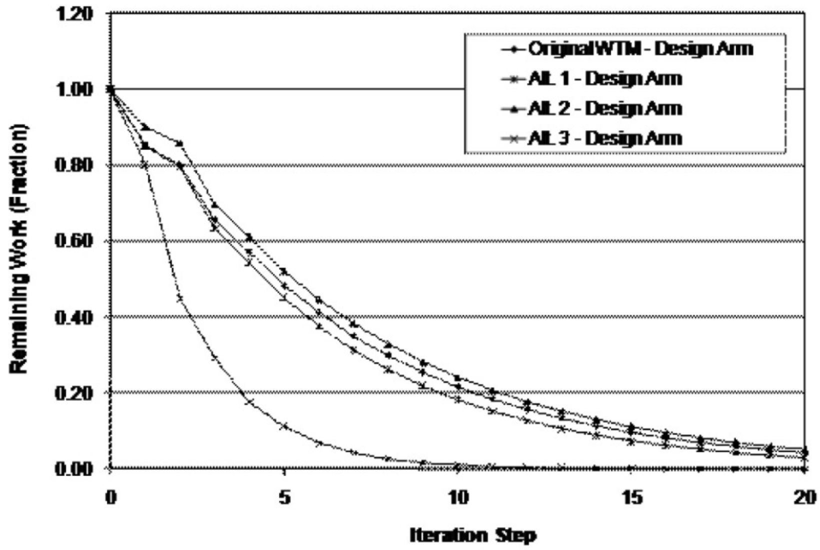

Figure 4. Dynamic response for the Design Arm task showing remaining work at each iteration stage for various WTM models

Figure 4 shows an example dynamic responses of one of the individual tasks (Design Arm) to compare the resulting responses of the original WTM model of the design process with the three alternative models. All three models, as previously determined, show a stable design process, with completion of the manipulator design within 15-20 iterations. With the exception of the third alternative, all the dynamic models show very similar responses. The third alternative WTM model shows iterations occurring faster than the others. Additional tasks that were considered in this model were Consider Stability Criteria, as well as Design Robot in CAD. These tasks were medium and strongly dependent respectively on Tasks C-F. Also, the former had a strong feedback dependence to Task I (Factor of Safety). These dependencies could indicate that this group may have made several considerations early in the design process (perhaps during the ideation/brainstorming phase and noting that these new tasks would be among the slowest converging) that would have constrained the rest of the design, thus reducing the number of iterations overall required to complete the project.

6. Unexpected Disturbances

As with any design process, random, unexpected or unpredictable events can occur at any time resulting in delays in arriving at a feasible solution. These may include late customer requests or a failure of an agent, and their degree ranging from mild to fatal, causing an interruption in the design process, and delaying results [Matthews and Lomas 2008].

6.1 Mathematical Formulation

In order to model the design process to include random disturbances, Eq. 1 is modified as follows:

$$\mathbf{u}_{t+1} = \mathbf{A}\mathbf{u}_t + \mathbf{B}\boldsymbol{\delta}_t \tag{6}$$

where **B** is the Disturbance Transformation Matrix (DTM) [Matthews and Lomas, 2008], and $\boldsymbol{\delta}_t$ is the disturbance input at iteration *t*. The elements of $\boldsymbol{\delta}_t$ represent the introduced random events to the design process as additional levels of rework on the tasks to which such disturbances were introduced in order to complete them. The examples shown herein will consider a few tasks having unexpected events introduced to them. There are several possibilities for the DTM, including the form $b_{ij} = b_{ji}^{-1}$, representing pair-wise negotiation of tasks to minimize pair-wise impact, but not necessarily global impact [Matthews and Lomas 2008]. For simplicity, **B** = **I**, where **I** is the identity matrix used herein.

6.2 Results

Examples of the resulting dynamic responses for the design process of the tire and wheel mechanism are presented. Unexpected events of varying rework levels were introduced to the first four tasks (those pertaining to the design of the manipulator itself). The effect of these unexpected events on the design process in terms of the number of iterations needed to complete the design tasks was analyzed.
Figure 5 shows the responses of the design process when 100 percent additional work is introduced into Tasks C-F at the 5th and 10th iteration respectively, a worst case scenario for this design process.
Table 6 summarizes several results from disturbances introduced to Tasks C-F at both the 5th and 10th iteration, comparing the number of iterations further required to complete the design project and the total number of man-hours needed by each group member at each iteration (using the best and worst case design task durations). Also, the average number of iterations required per week is shown, increasing from 1.54 when there are no unexpected events, to ~2 iterations per week for the worst case scenario (100 percent additional work introduced). As such, if the number of iterations per week remained the same as that for no unexpected events, the design process would need an additional 2 weeks, which is not acceptable given the limited length of time the academic semester lasts, and that student groups normally would have 11 weeks in which to complete the design project.

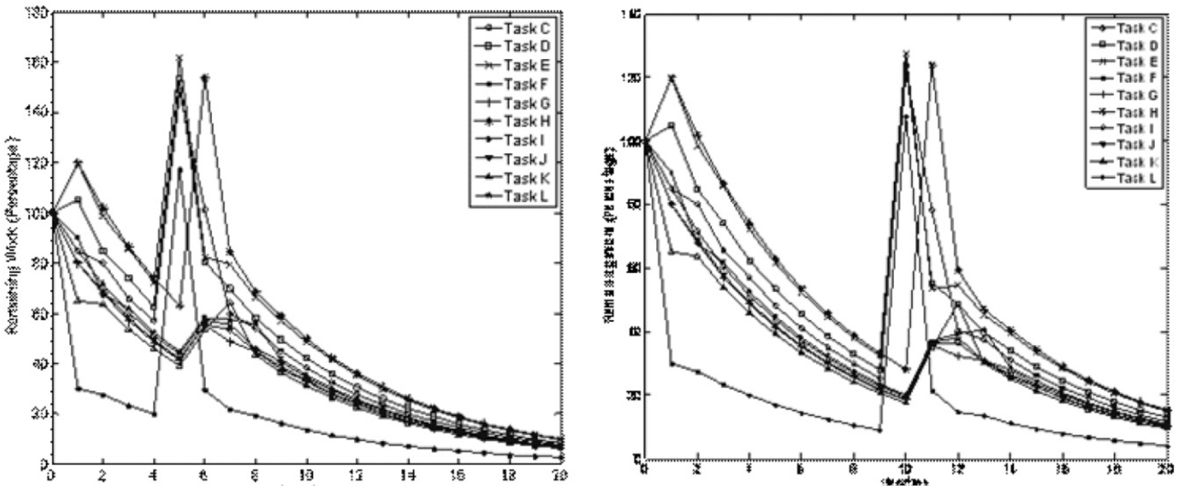

Figure 5. Dynamic response for the design process of the tire and wheel manipulator with disturbance of 100 percent introduced to Tasks C-F at 5th (left) and 10th (right) iteration

Table 6. Task Duration in Man-Hours/Week (6 Person Groups) With and Without Disturbances

Disturbance Occurrence	**Amount of Disturbance (additional work added)**	**Iterations Required to Complete Design**	**Best and Worst Case Design Duration**	
			No. Iterations/Week	**No. Man Hours/Week**
No disturbance	0 %	17	1.54	4.8, 11.4
5th iteration	25 %	18	1.63	5.3, 12.4
	50 %	19	1.72	5.7, 13.5
	100 %	20	1.82	6.6, 15.6
10th iteration	25 %	19	1.72	5.3, 12.4
	50 %	21	1.91	5.7, 13.5
	100 %	23	2.09	6.6, 15.6

7. Conclusions

In this paper, existing product design and development methods were applied in evaluating the design process of a third-year engineering design project. First, an extension of the design structure matrix, the work transformation matrix, was used to show dependency strength between iterative tasks. From this matrix, the eigenstructure was determined and the most significant modes were examined to determine which tasks contribute the most work in the design process. Further, the total work performed for each task was added up to confirm this finding. Second, a sensitivity analysis was performed using alternative DSM-WTM matrices determined by the students in the third-year course, from which the eigenstructures as well as the dynamic responses were compared to that of the original matrix. Also, task duration times, total number of iterations, and total design project duration were estimated by the students, with results being within originally predicted quantities. Finally, the effects of unexpected events were investigated on the dynamics (and ultimately, the duration) of the design project by introducing random disturbances to a few tasks at various stages of the design process and at various degrees in terms of additional work required due to the unexpected events. The effects of the random disturbances were measured in terms of the number of additional iterations required, as well as when the impact of these disturbances would be greatest. This information would be useful to both instructors and students, should changes to the design project, such as specification changes, need to be made during the term. Project completion delays can be estimated as a result of these changes, and resource reassignment may be determined to alleviate such delays.

Using DSM-WTM methodologies to analyze an academic design project is useful, as it provides instructors with a quantitative sense of the level of difficulty and feasibility of the project during an academic term, with such an analysis useful to both existing, as well as introducing completely new design projects to students. Not only is this analysis useful to students to assist them with organizing and tackling tasks more efficiently, instructors can also foresee more clearly the window of opportunity they have before implementing design project changes, as well as to better prepare them in mitigating project delays due to unknown causes. Finally, this design process model also provides a basis for quantifying process resource redistribution via closed-loop control.

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References

Barari, A. and Pop-Iliev, R., "Reducing Rigidity by Implementing Closed-loop Engineering in Adaptable Design and Manufacturing Systems," Journal of Manufacturing Systems (accepted), 2009.

Cronemyr, P., Rönnbäck, A.Ö., Eppinger, S.D.,"A Decision Support Tool for Predicting the Impact of Development Process Improvements," Journal of Engineering Design, Vol. 12, No. 3, September 2001, pp. 177-199.

Eppinger, S.D., Whitney, D.E., Smith, R.P., and Gebala, D.A., "A Model-Based Method for Organizing Tasks in Product Development," Research in Engineering Design, Vol. 6, No. 1, 1994, pp. 1-13.

Kim, D., "On Representations and Dynamic Analysis of Concurrent Engineering Design," Journal of Engineering Design, Vol. 18, No. 3, June 2001, pp. 265-277.

Ong, K.L., Yee, S.G., and Khoo, L.P., "Homogeneous State-Space Representation of Concurrent Design," Journal of Engineering Design, Vol. 14, No. 2, June 2003, pp. 221-245.

Lee, S.G., Ong, K.L., and Khoo, L.P., "Control and Monitoring of Concurrent Design Tasks in a Dynamic Environment," Concurrent Engineering: Research and Applications, Vol. 12, No. 1, March 2004, pp. 59-66.

Matthews, P.C. and Lomas, C.D.W., "A Methodology for Quantitative Estimates for the Work and Disturbance Transformation Matrices," Journal of Engineering Design (iFirst online article), September 26, 2008, pp. 1-13 (http://www.informaworld.com/smpp/content~db=all?content=10.1080/09544820802310909).

Prasad, B. Concurrent Engineering Fundamentals: Integrated Product and Process Organization, Volume I. Prentice Hall, 1996.

Smith, R.P. and Eppinger, S.D., "Identifying Controlling Features of Engineering Design Iteration," Management Science, Vol. 43, No. 3, March 1997, pp. 276-293.[1]

Smith, R.P. and Eppinger, S.D., "A Predictive Model of Sequential Iteration in Engineering Design," Management Science, Vol. 43, No. 8, August 1997, pp. 1104-1120.[2]

Dr. George Platanitis
Design Lecturer/Engineer
University of Ontario Institute of Technology, Faculty of Engineering and Applied Science
2000 Simcoe St. N., Oshawa, Canada
Telephone: +1 (905) 721-8668 x2866
Telefax: +1 (905) 721-3268
Email: george.platanitis@uoit.ca
URL: http://engineering.uoit.ca