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MODELLING AND CONTROLLING COUPLED, CONCURRENT DESIGN TASKS SUBJECTED TO EXTERNAL INFLUENCES

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Abstract

Intense competition has forced many designers and manufacturers to drastically reduce product development cycle time. Many organizations have responded by implementing concurrent engineering concepts with credible results. Despite these initiatives, complex product design and development remains a technical and organizational challenge. Proven techniques have traditionally been applied to design task planning. However, these techniques assume a uni-directional, linear progression of design activities, with no information feedback (or feed-forward), and cannot handle dynamics changes in the design environment and unscheduled interruptions to the design tasks. In reality, a design task is very complicated as it is dynamic and iterates from one stage to another. In product development, it is common for coupled, concurrent design tasks to iterate several times before the entire product development process is completed, leading to delays in product launches and cost over-runs. Furthermore, unexpected disturbances may destabilise the entire product development process. State-space control theory is used to model these coupled, concurrent design tasks and to predict and control the stability and convergence rate of the design tasks. The generalised model can determine the volume of work remaining for each design task at every stage of iteration, and predict the number of iterations before all the tasks are completed. A case study of the design of a printed circuit board burn-in chamber is discussed.

Keywords: concurrent engineering, design management, integrated and distributed product design, state space.

1 Introduction

The design of a complex product often involves inter-related tasks. The immense volume of information to be monitored and managed is more than any single individual can handle. It therefore makes sense to reduce the complexity of the product's design, by decomposing it into smaller, more tractable tasks. The decomposition of the design activity into structured sub-units or tasks has been undertaken as a first step in modelling and analysing the design process. Not only are there fewer tasks to manage, the information shared among them is considerably easier to track and manage. The relationships among these tasks, including the information processed by and transferred among them, form the structure of the design process [1].

Besides the immense volume of information involved, information flow between inter-dependent design tasks is such that the actions of one task impinge on the other. Thus, *design iterations* are inevitable. In a design iteration, design decisions made based on incomplete or imperfect information are re-visited [2]. There are several reasons for this. Firstly, rework is clearly necessary if the tasks which were completed earlier are not compatible with the new information generated by the later tasks. Secondly, external factors may have caused an unanticipated change to the design objectives or parameters, over which the designer has no control. All these can lead to long product development times. For instance, between 13% to 70% of the total development time of Intel Corporation's semiconductor projects can be traced to design iterations [3]. Consequently, the modelling and analysis of design iteration is of great importance in the management of design projects.

Many process models of the design process have been developed. One popular representation is the *directed graph* (or digraph) [4] which consists of nodes, representing the tasks, connected by arcs or directed lines, representing directed information flow. Another common graphical representation is *PERT/CPM* by which the 'critical path' of a project and the most optimistic completion time may be ascertained [5]. The Structured Analysis and Design Technique SADT [6], [7] which later evolved into the IDEF representation [8], is more formal than the digraph representation. *IDEF* models Computer Integrated Manufacturing (CIM) and Concurrent Engineering (CE) activities through a sequence of activities and relationships among them. The *Petri net* and its derivatives, applied most commonly to computer and manufacturing systems, verifies if a process is feasible [9], [10]. Agent-based simulation tools such as *Virtual Design Team* (VDT) [11] assess the effect of the structure of an organisation on process execution. However, these methods cannot explicitly display circuits of information or iterations and can only efficiently process a limited number of tasks or activities.

A more compact representation of the design process is the *design structure matrix* (DSM) first introduced by Steward [1]. The DSM overcomes the size and visual complexity of the above-mentioned graphical techniques, because the DSM clearly shows the task dependencies and the information loops. DSM has been widely applied in real engineering projects, for example, automotive brake system [12], semiconductor [13] and jet engine design [14]. It has also been adopted widely in modelling engineering design tasks [13], [15], in the integrated analysis of engineering design management [16], [17], and in design iteration analysis [18], [19]. Based on the DSM, Smith and Eppinger [20] developed a method using linear systems theory to analyse and identify 'controlling features' of the concurrent design process. They postulated a numerical DSM called the Work Transformation Matrix (WTM), a fully parallel iterative structure, in which all the design tasks are executed concurrently at each stage of iteration. The measure of the strength of dependency between tasks is the percentage of re-work created for one task by work performed by other inter-dependent tasks. McDaniel [21] expanded the WTM by incorporating work-load policies. The status of the design process and resource usage may be tracked at every stage. Joglekar *et al*. [22] extended McDaniel's model to the systems (managerial) level.

However, these and other analytical methods are inadequate in controlling design processes which are dynamic and subject to unexpected influences. For instance, an external disturbance such as a competitor's initiatives may necessitate a re-examination of the entire design project in order to reduce costs or shorten the product development cycle time. Resources may have to be re-allocated among the various design tasks to achieve this goal. Other examples of such influences include improvements in technologies and changing customer preferences. Because of the impact of uncertain influences, the stability of the entire design project may be jeopardised. Therefore, it is imperative that the entire product development is stable (i.e. all design tasks are completed within an expected period of time.). In complex design projects, it is therefore important to ascertain the unstable tasks even before they begin. Sometimes, it is not sufficient to know if a process is naturally stable. In the view of the authors, it is just as important to identify tasks that consume an enormous amount of resources and time even before they begin. This paper discusses a generalised state-space control model of coupled, concurrent design tasks proposed to model and to control the stability and convergence rate of the design iterations. If applied early in the planning of design tasks, those tasks that require many design iterations to complete or that can run out of control can be identified and rectified early.

3 The state equations for concurrent design iteration

A design process comprising n tasks is represented as an $n \times n$ design structure matrix (DSM). Readers may refer to several literatures on how to read a DSM [1], [13], [15]. Concurrent design iteration can be expressed in the state equation as follows

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) \tag{1}$$

where the index k, the discrete-time variable, takes only a finite number of values representing the number of stages of iteration. State matrix $\boldsymbol{A}$ is the DSM which embodies the numerical relationships of tasks, while the matrix $\boldsymbol{B}$ embodies data on external input or control input, $\boldsymbol{u}(k)$, e.g. engineering changes, process disturbances, financial cut-backs, resource re-distribution, etc. Each state variable x_i in the state vector $\boldsymbol{x}(k)$ represents the output of a design task i. The unit of measure of a task's output can be cost, time, design specifications, mechanical or electrical parameters, etc. To develop a generalised model, the volume of work is chosen as the unit of measure of output. In this research, the measure of task input is the same as the task output's, e.g. if the task output is measured in terms of work, then the task input is also in terms of work. For a more complex system, the elements of the $\boldsymbol{A}$ matrix can be of different units of measure because of the variety of task inputs and also because they relate inputs of different dimensions, for example, between dollars and percentage of work.

The open-loop system described by Equation (1) is called the *Non-Homogeneous State-Space* representation (NHSS) of concurrent design tasks. It is called non-homogeneous because external inputs are modelled. A system is said to be homogeneous if there are no external inputs and the system response is due only to initial conditions. The *Homogeneous State-Space* representation (HSS) of concurrent design task is expressed as

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) \tag{2}$$

The following three assumptions are made before linear algebraic analysis can be performed [20]:

- All tasks are executed concurrently at every stage.
- The quantum of re-work of a task is a linear function of the work done by other coupled design tasks.
- The elements of the state matrix (i.e. the strength of dependency of tasks) do not vary with time.

3.1 Stability of tasks

The stability of the homogeneous or undisturbed system may be gauged from the eigenvalues and eigenvectors of state matrix $\boldsymbol{A}$. The eigenvalue matrix $\boldsymbol{V}$ has n diagonal elements, each of which, l_n, represents an eigenvalue of the $\boldsymbol{A}$ matrix, assuming n distinct eigenvalues. The $n \times n$ eigenvector matrix $\boldsymbol{S}$ consists of column vectors $\boldsymbol{S_j}$ (j = 1, 2… n) each of which is an eigenvector which is associated with one of the eigenvalues l_n (e.g. $\boldsymbol{S_1}$ with l_1). An eigenvector embodies a *mode shape* of the system [24]. In concurrent design iteration, the mode shape is also known as the *design mode* [20]. A design mode is a group of intimately related design tasks which create significant work, directly or indirectly, for each other. The superposition of all the mode shapes makes up the response of the system. Each mode shape ($\boldsymbol{S_j}$) is represented by the relative fractions (i.e. the elements) s_{ij} (i = 1,2,…n) in a column, each of which corresponds to a state variable (i), or to a task's state/output. The eigenvector corresponding to each eigenvalue characterises the relative contribution of each of the tasks to the total work. The most slowly converging or diverging design mode, i.e. the critical design mode, corresponds to the eigenvalue with the largest real value. In concurrent design iteration, everything hinges on the critical design mode and its critical eigenvector while the slowest task is the task with the largest number in the critical eigenvector [25].

While the eigenstructure of the state matrix reveals the dominant response shape of tasks, the location of an eigenvalue in the complex plane reveals the expected type of response. From the location of the eigenvalue in the complex plane, the system can be ascertained to be stable (convergent), unstable (divergent), or oscillatory (recurrent re-work) [25]. Obviously, convergent tasks with steady workload are most desirable because they are stable. A state matrix's eigenstructure gives some insight into the stability of concurrent design tasks. The natural (or undisturbed) response of the system can be determined even before the first design task begins. A natural response is a response of the system over time without any external disturbance. In reality, real life systems are subject to unexpected external disturbances. Thus, it is essential to monitor and control all design tasks simultaneously. A case study of the design of a PCB burn-in chamber in an electronics manufacturing firm is discussed to demonstrate the applicability of the proposed models in analysing and monitoring the stability of design tasks under the influence of unexpected disturbances.

4 A case study

An electronics manufacturer and an affiliated company collaborated intensively and concurrently to design a Burn-in Chamber for the cyclical heating tests of printed circuit boards (PCBs). The chamber functions as a heating enclosure where air temperature and circulation are measured and controlled by an electrical and electronic system via a PC. The PCBs are mounted on a rack called the PCB cage which is secured in the chamber during the cyclical heating tests. A picture of the Burn-In System is shown in Figure 1. While one company focused on the mechanical aspects of design, the other concentrated on the electrical and electronic aspects. This case study focuses on the mechanical aspects, from planning to delivery of the first prototype. The authors define a design task as beginning with defining the functions and specifications of the artefact to detailed design and final prototyping.

At the very start of the project, the two development teams met intensively to finalise an overall development schedule. The planned schedule was divided into 3 major sections, i.e. conceptual design, detailed design and prototyping. Immediately after the development schedule was approved by management, the two teams constructed the basic architecture of the Burn-in System. The mechanical system has two main parts: a chamber and a PCB cage. The design of mechanical system is decomposed into 12 subsystems: Heating & Cooling, Circulation, Structure of Chamber, External Ventilation, Wiring of Chamber, Structure of

PCB Cage, PCB Mounting, Optical Sensor Positioning, Wiring of PCB Cage and Maintainability of PCB Cage. The 12 sub-systems were designed concurrently because the 3 design engineers from manufacturing, R&D, and electrical & electronics were known to be able to work with each other. These 3 engineers were considered the main resources employed by the project. The design project started on the 3rd week of January 2002 and was scheduled to be finished with the delivery of the prototype at the end of April 2002 on week 13.

Figure 1. Finished Alpha Prototype of the Burn-in System (Chamber with PCB Cage inside)

4.1 Data acquisition

After the twelve design tasks were defined, the authors interviewed the 3 engineers for all the information necessary to construct a state matrix. For instance, they were asked to spell out the precedence relationships among the 12 design tasks and to estimate the cycle time of a complete iteration of each task. An iteration is a design cycle during which some design action is undertaken to finish the work that was generated by other tasks during the immediately-preceding stage of iteration. In a *complete* iteration, 100% of the remaining work is attempted; for example, at the initial execution of a design task. The reasons of iteration are many: assumptions and imprecise information, re-use of old information or concepts, intrinsic iteration in computation or analysis. A state matrix, similar to the Work Transformation Matrix (WTM), was obtained as shown in Table 1. A WTM is a numerical DSM in which the strength of dependency between tasks is measured by the percentage of re-work created for a task as a result of work performed by other inter-dependent tasks. For example, in Table 1, the element in 3rd row and 1st column means that task 1's relationship to task 3 is such that task 3 has to redo 5% of its work after task 1 undergoes a complete iteration. An initial HSS analysis of all 12 design tasks can now be undertaken. The engineers were asked to record the time taken by each and every task to finish each iteration, and the proportion of remaining work after every stage of iteration.

Table 1. State Matrix of Burn-in System Design

Design Task	Time (hour)	ID	1	2	3	4	5	6	7	8	9	10	11	12
Heating & Cooling	56	1	0	0.3	0	0	0	0.3	0.05	0.1	0	0	0	0
Circulation	56	2	0	0	0.1	0	0	0	0.05	0.05	0	0	0	0
Structure of Chamber	40	3	0.05	0	0	0	0.1	0.05	0.3	0.1	0	0	0	0
External Ventilation	56	4	0.3	0.3	0.05	0	0	0.3	0	0	0	0	0	0
Wiring of Chamber	8	5	0.3	0.3	0.1	0.1	0	0.1	0.3	0	0	0	0	0
Safety	24	6	0	0.05	0.1	0.1	0	0	0	0	0	0	0	0
Maintainability of Chamber	8	7	0.1	0.1	0.1	0	0	0	0	0	0.1	0	0	0
Structure of PCB Cage	56	8	0	0	0.3	0	0	0	0	0	0	0.3	0.1	0.1
PCBA Mounting	112	9	0	0	0	0	0.3	0	0.3	0.3	0	0.1	0	0
Optical Sensor Positioning	16	10	0	0	0	0	0	0	0	0.3	0.3	0	0	0
Wiring of PCB Cage	8	11	0	0	0.1	0.3	0	0	0.3	0.3	0	0.3	0	0
Maintainability of PCB	16	12	0	0	0	0	0	0	0	0	0.05	0	0	0

4.2 The natural response and convergence rate of tasks

The state matrix's eigenstructure predicts a stable and convergent natural response of all 12 design tasks (see Figure 2). It can be seen from Figure 2 that, assuming that all 12 design tasks started off with 100% of work, the remaining work of all tasks decreased after every stage of iteration, except task 11 (Wiring of PCB Cage), task 5 (Wiring of Chamber) and task 9 (PCB Mounting) at their first stage of iteration. There are several reasons for this. The wiring work is constrained by the fact that other structures and systems must first be in place before it can commence, while the PCB cage design must be completed before the design of the PCB mounting can proceed. According to the critical eigenvector of the state matrix, the slowest task was task 11 (Wiring of PCB Cage) with the largest value in the critical eigenvector – 0.5647. The earliest possible completion of the entire project hinges on task 11. Table 2 shows the predicted natural response of the entire mechanical system design with timeline, given that task 11 is the slowest-converging task. The entire mechanical system design is deemed to be completed when the alpha prototype is delivered, i.e. by week 13 (the 4th week of April 2002). However, from Table 2, the remaining work of task 11 by week 13 is approximately 13%. If delivery is enforced on week 13, only 87% of task 11 will have been completed. Thus, the completion state of task 11 was set at x_{c11} = 0.13. That is to say, at the time of scheduled completion, the remaining work of each and every of the 12 design tasks should not exceed 13%. Since the alpha prototype was built with production-intent parts, i.e. parts having the same geometry and material properties as those in actual production, but not necessarily fabricated by the same manufacturing process, 13% of remaining work is considered acceptable. Since it is intuitive that the time needed to execute a stage of iteration depends on the amount of work to be done at that stage of iteration, the time elapsed for each succeeding stage of iteration is shorter and shorter. The convergence rate of each task, from the slowest to the fastest, is shown in Table 3. Task 11 was the slowest for the afore-mentioned reasons, while task 12 was the fastest since it only slightly depended on task 9. Tasks 11, 9, and 10 were the 3 slowest tasks because they were not only dependent on the PCB cage design, but also on the design of the chamber as well, since the chamber design determines the allowable space for the PCB cage.

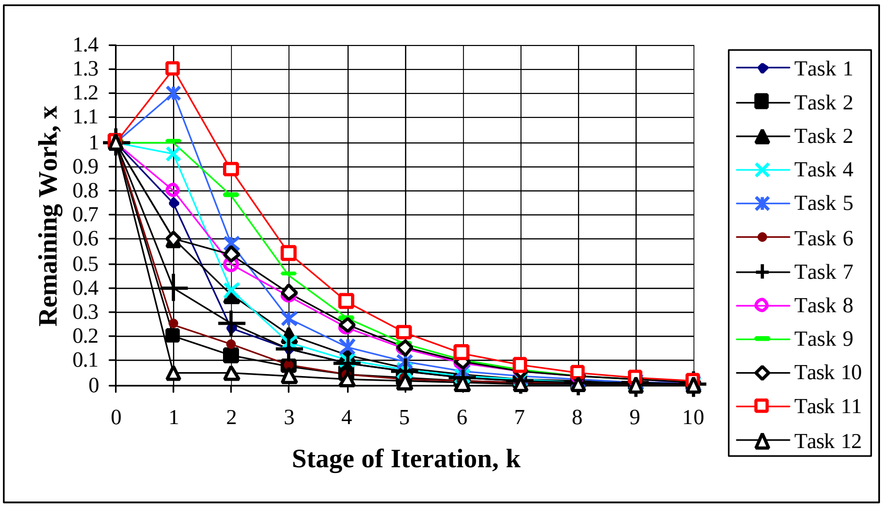

Figure 2. Natural Response of Burn-in System Design

Table 2. Natural Response of the Entire Mechanical System

Stage of Iteration, *k*	Remaining Work of the Slowest Task (%)	Cumulative Time Elapsed (hours)	In Week #	Status
0	100	392	3.3	
1	130	784	6.5	
2	89	1090	9.0	
3	54	1268	10.6	
4	34	1376	11.5	
5	21	1442	12.0	
6	13	1483	12.5	Planned completion

Table 3. Convergence Rate of Tasks

Design Task (Slowest to Fastest)	11	9	10	8	5	3	4	1	7	2	6	12
Degree of Satisfaction of Engineers (1-least. 10-most.)	2	4	6	6	3	7	7	8	8	7	8	8

4.3 Actual vs predicted schedule

After all 12 design tasks were completed, the three engineers were asked for their views on the convergence rate of each design task. The 2nd row of Table 3 expresses their impressions of the convergence rates of the 12 tasks. Intuitively, at a given stage of iteration, fast converging tasks will result in less remaining work than slower converging tasks, and therefore the degree of concurrence would be greater. It can be seen from Table 3 that there is a correlation between the degree of concurrence and the convergence rate of tasks. Tasks 5 and 11, however, posted relatively low satisfaction primarily because, besides the 12 design tasks of the mechanical system, they were also dependent on the design of the electrical and electronic system, which was still in progress.

The entire project ended after week 17, four weeks later than planned. Two disturbances were encountered in the course of the project. The 1st disturbance happened in week 9 when the

R&D engineer resigned. The 2nd disturbance occurred in week 13 when the company encountered a production bottleneck. Faced with these 2 unexpected disturbances, the HSS had to re-assess the completion date of the project. The resignation of the R&D engineer caused the project to languish for 2 weeks. During these two weeks, the new R&D engineer familiarised himself with the work undertaken by his predecessor, while the development team reviewed the design accomplished up to that point in time. Thus, no additional resources were assigned to the project. However, although the head-count remained at three, in reality, the third person was too new on the job to be able to contribute effectively. The second disturbance gave rise to competition for human resources between production and design, leading to a work stoppage of another week, as the manufacturing engineer and the new R&D engineer were assigned to help out in production. After the week was up, all three engineers continued to work on the project.

The response of the overall project with the 2 disturbances is tabulated in Table 4. Compared to the natural response in Table 2, the disturbed response requires two more stages of iteration – 7 and 8. The 1st disturbance occurred after the 2nd stage of iteration, and so the remaining work of all tasks after the 2nd stage of iteration was not attempted in the 3rd stage of iteration. Instead, this remaining work was attempted in the 4th stage of iteration, giving rise to the 2-week delay. The same is true of the 2nd disturbance which happened after the 4th stage of iteration, except that the delay was only one week in this case. From Table 4, we see that the project can only be finished in week 15.4. In reality, the project was actually delayed for 4 weeks from the planned completion in week 13. Thus, the deviation of the predicted (week 15.4) to the actual (week 17) completion date is less than 10%. This deviation is acceptable, considering the fact that minor disruptions and other delays were not taken into account.

Table 4. Response Analysis of the Entire Project after the 1st & 2nd Disturbances

Stage of Iteration *k*	Slowest Task's Remaining Work (%)	Cumulative Time (hours)	In Week #	Status
0	100	392	3.3	
1	130	784	6.5	
2	89	1090	9	1st disturbance due to resignation of the R&D engineer (project suspended for 2 weeks).
3	89	1330	11	New R&D engineer familiarises himself with his predecessor's work
4	54	1508	12.6	2nd disturbance due to production bottleneck (project suspended for 1 week as 2 engineers helped relieve the production congestion).
5	54	1628	13.6	Revisiting work done in the previous stage.
6	34	1736	14.5	
7	21	1802	15	
8	13	1843	15.4	Predicted completion after 2nd disturbance.

It should be remembered that no extra manpower resources were employed to expedite the disrupted design project. That being the case, it is in management's interests to monitor and control the project to minimise the effects of disturbances. The non-homogeneous state space analysis is one way to do this. A non-homogeneous state-space model can monitor and control a system's response to forced perturbations, whether externally or internally generated. It is expected to stabilise unstable systems and to improve the convergence rate of design tasks. In their ongoing research, the authors explored this and other analytical techniques which can better manage engineering design process.

5 Concluding remarks

A linear state space representation of concurrent design tasks is proposed. The homogeneous state-space representation (HSS) of concurrent design tasks analyses the degree of stability and convergence rate of the entire design process**.** A case study of the design of a PCB burn-in system was discussed to illustrate how HSS can be applied in modelling and analysing the 12-task design project in the face of unexpected disturbances. Disturbed response of tasks can be modelled while slowly converging tasks can be identified. Completion of the project after disturbances was predicted with a less than 10% deviation from actual completion. However, no additional resources were employed to improve and control the disturbed design project. In the non-homogeneous state space analysis, more meaningful results can be obtained as it can monitor and control a system's response to forced disturbances.

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