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Usability of the design structure matrix for automotive design engineering

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Usability of the Design Structure Matrix for Automotive Design Engineering

by

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Bachelor of Mechanical Engineering, University of Engineering and Technology Lahore, October 1996

A thesis

presented to Ryerson University

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Usability of the Design Structure Matrix for Automotive Design Engineering

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Muhammad Adrees

Submitted to

The Department of Mechanical Engineering in partial fulfillment of the requirement for the Degree of Master of Applied Science in Mechanical Engineering, Ryerson University, 2003

Abstract

In this thesis the author discusses the Design Structure Matrix (DSM) as a best practice. The DSM provides project management structure, develope and modularises the systems level design of products, performs project scheduling, tasks interdependency, resource allocation, dependent tasks planning, and provides proper communication and coordination structure.

The DSM tool is applied to two case studies of the design of a gasoline/electric hybrid vehicle power train and one case study of assembly design, with concentrated emphasis on the recommendations on how the specific cases in this thesis can benefit. A novel analytic feature Relative Significance Summation Clustering (RSSC) of the DSM is also identified, which appears to be otherwise unreported in the literature.

The case studies analysis demonstrates that the DSM tool can be used to develop a deeper understanding of the system level design, project management, and assembly design. The DSM tool was successful at providing a representation of many of the issues and insights identified in the case study analysis.

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Chapter 1 Introduction

This thesis reports on work carried out as part of the Automobile of the 21st Century Network of Centres of Excellence (Auto21) and deals with best practices in design engineering. It focuses on one particular best practice, the *design structure matrix*, as applied to automotive design engineering.

Best practices are a topic of general interest in industry, because they represent superior modes of behaviour that lead to better corporate performance. Intuitively, it seems obvious that all engineering enterprises seek the best possible practices to remain competitive and to ensure the highest possible quality and safety of product in a given context. Thus, achieving a sound understanding of what constitutes a best practice and how they can be used in real-world design engineering settings is important. However, there has been almost no phenomenological research on best practices. Indeed, there is no single field into which the study of best practices falls. This is because the best practices approach is in essence a generic problem-solving method, which applies equally well in any area where "problem-solving" leads to new organizational norms.

Existing research that has attempted to identify best practices has been limited to health management, manufacturing, and management sciences. These efforts will be discussed subsequently. Even so, there are problems with the reported research (discussed below) that prevent it from being used in design settings. Virtually no work has been done in product development and design engineering.

There is no well-accepted definition of the term "best practice", and there is no body of knowledge on how best practices are identified, or created, or specified, or on how best practices, once identified, can be transferred between organisations. If there were such a body of knowledge was available, there would be many benefits (which are discussed below).

As a result of the nature of the Auto21 project in which the author was involved, the author identified one specific best practice that was applicable to design, the *design structure matrix*. This one best practice will be the focus of this thesis.
There are two reasons for this:

1. After about one year, and due to circumstances beyond the author's control, the goals and intention of the Auto21 project changed.
2. The notion of "best practices" is so broad and so ill defined in the existing literature, that it was deemed beyond the scope of a Master's degree to continue without some specialisation.

Therefore, the focus of this thesis will be on the application of the design structure matrix on three automotive related examples. The goal is to demonstrate how the DSM can be easily used in a wide variety of automotive engineering problems. This will be done by describing three examples of the use of the DSM in the general areas of project management, systems design, and assembly design. Two of these examples will pertain directly to the Auto21 project; the third relates to a recent project by a Toronto-area product-engineering firm.

Deliverables include recommendations on how the specific cases used in the examples can benefit by the use of the DSM, a new analytic feature Relative Significance Summation Clustering (RSSC) of DSMs that has not yet been reported in the literature to the author's best knowledge, and a list of directions for future research for both DSM and best practices in general.

The rest of this thesis is organised as follows.

Chapter 2 provides background of Auto 21 and describes objectives and goals of the original and modified Auto21 projects. Chapter 3 describes the current state of best practices in engineering design, the currently available tools for identifying and implementing best practices, and discusses some best practices that have been found in the literature. Chapter 4 addresses the need of the Auto21 project to develop an infrastructure for project management and systems design by studying various modelling tools and identifying the design structure matrix as the best available tool. Chapter 5 discusses the use of the design structure matrix in automotive design and applies it to two situations in the Auto21 project, and one case study of a tailgate latch assembly for trucks. Discussion and conclusions of this thesis are given in Chapter 6.

Chapter 2 Background

The Automobile of the 21st Century (Auto21) is a national Network of Centres of Excellence (NCE) supported by the Government of Canada. Auto21 received a 4-year grant of almost $50 million, which, when combined with the industrial and institutional contribution of over $11 million, will help Canada to strengthen its global competitive position in research and development sector of automotive industry, which is largest industry and biggest provider of export earnings. Auto21 currently supports over 230 top researchers from 35 universities, government research facilities and private sector research labs across Canada and around the world.

The network is organized into six research themes including health and social sciences topics, materials science and manufacturing, power train engineering, fuel and emissions studies, design processes, and intelligent systems. There are 28 research projects in the six themes; each project is supervised by a project leader who coordinates the work of a team from at least three institutions in at least two provinces.

One of the original projects of Auto21 in the design theme was *Development of Best Practices and Design Methodologies for Rapid Vehicle Component Design*. It was intended to discover, capture, and codify best practices in the automotive parts industry. The author's role in this original project was to conduct a detailed survey of existing work in best practices and detail the research methodology for other graduate and undergraduate students working in this area.

The first stage of the best practices project involved interviewing industry representatives about best practices and design methods. This was done by the principal investigators. At the same time, the author conducted a literature survey of existing best practices and best practice methods. The author found little in the literature regarding best design practices that could be adapted to vehicle component design without significant effort.

Also, it became clear from the interviews that industry was unwilling to release information about proprietary internal processes. Instead, industry asked to improve the educational experience of students – to help train students by giving them educational experiences derived from the automotive industry.

After one year working on a best practices theme, the project team changed its research direction to address these findings.

The new project would find a near-future general technology, and would develop an intensive multidisciplinary student project based on that technology. The new direction would leverage an existing student project from the University of Sherbrooke, called *Reflex*, a gas/electric hybrid minivan. The general objective of the Reflex project was to design and build a gas/electric power train to be installed in a 1996 Dodge Caravan SE (made available by a sponsor to the Reflex team). The minivan was to be entered in the Michellin Challenge Competition in August 2003.

Specific objectives/goals

The Auto21 project team was to help the Reflex team to develop such a power train system, and eventually refine and redesign it after the Michellin competition. In consultation with the Auto21 team, the Reflex participants developed a number of more specific goals for their project.

- Develop a high efficiency, low weight regenerative braking system.

One of the most important differences between a hybrid vehicle and a conventional vehicle is the ability of the hybrid vehicle to reclaim a portion of the energy otherwise lost to braking. The concept of regenerative braking system is that when the driver brakes, the motor becomes a generator, using the kinetic energy of the vehicle to generate electricity that can be stored in the battery for later use. A hybrid vehicle with regenerative braking can save a great deal of energy when compared to traditional cars, especially in "stop-and-go" driving situations. For example, the Toyota Prius reclaims approximate 30% of the kinetic energy typically lost as heat to friction brakes.

- Develop or adapt a continuous variable speed transmission (CVT) to reduce mass and volume and optimize the efficiency of the internal combustion engine.

A CVT varies the transmission ratio continuously through the use of belts instead of gears, so that it is an automatic transmission with an essentially continuous gear ratio. As a result, the gear ratio can be kept at an optimal value for performance and energy efficiency over a large range of operating conditions. CVTs have an efficiency range from 85 to 92%. The use of a CVT is an innovative way of linking a power system to automobile wheels. The latest development of the automotive transmission shows the interest of the CVT for internal combustion engines. In order to deliver high torque at different speeds, CVTs are a good choice. For example, the Honda CVT substantially increases the energy efficiency of its engine. Using the engine under its best performance characteristics allows the reduction of the maximum power delivered by the motor while reducing its fuel consumption. The use of CVTs for gas/electric hybrid power trains is a new field, and there remains a great deal of work to be done to develop good designs.

- Select internal combustion engine and develop its control system, optimize its thermodynamic cycle, and replace the flywheel by an electric motor/generator for proper vehicle motorization.

Over the past 100 years, internal combustion engines have been substantively optimised. They represent the best power system available for high power. The engine selected by Reflex for the minivan power train is the engine of the Toyota Echo. It was chosen for its compact size, power (more than 70 kw), and low emissions. It is also lighter and smaller than a conventional Dodge Caravan engine. It is available in Canada and the price for a used one is under $3000 including all subsystems. It was to be used as the main power system at high speeds, and as a supplement of power to the electric system at low speeds.

Flywheels can be used also for this purpose, but they are very complex, heavy, and large for small vehicles. Although flywheels are being used in some bus applications today, more work needs to be done to make flywheels safe and effective for hybrid vehicle automotive applications. In addition, there are some concerns regarding the safety of a device that spins at high speeds. Some alternative for temporary energy storage is necessary.

- Select a proper electric reserve system (battery pack) and design its recharging system.

The battery system strongly impacts both power capacity and overall mass of vehicles that use them They are, however, extremely "clean" sources of energy. The battery pack must allow the vehicle to operate under a 100% electric mode for some distance. Indeed, the Reflex team set on themselves the hard constraint that their vehicle must achieve zero emissions in city driving. This essentially means the vehicle must be able to run on only electric power for some distance.

Reflex selected Nickel-Metal Hydride batteries (Ni-MH). The Ni-MH batteries are used in several hybrid vehicles (Toyota Prius, Honda Insight). These batteries are less dangerous than Lithium-Ion batteries and more easily controlled. Also, Ni-MH batteries have a much longer life cycle than lead acid batteries.

The Auto21 team would help the Reflex team by involving students from other universities to design and build a power train meeting the objectives given above. Once the current Reflex test vehicle was complete, the Auto21 team would start a new version of the system based on the Reflex design.

The general goal for the Auto21 team was to use the Reflex project to train as many students as possible in some of the aspects of gas/electric hybrid vehicle design. This would prepare them for entry into a new area of automotive engineering that is seen as a significant future technology in automotive engineering. In exchange, the Reflex project team would provide a baseline design and some of the management infrastructure necessary for the collaboration.

The author's role would have been to consider the problems of project management and systems design, and to identify and implement suitable management and design tools for the collaborative Auto21/Reflex project. This was not seen as a simple exercise because of the numerous constraints on the problem, such as the availability and level of expertise of students, their geographical locations, and the technologies available in an academic environment.

Having considered a number of systems for representing design process, the author and his advisor identified the *design structure matrix* (DSM) as the best tool to help organise the Reflex project and work on its systems design components. The author therefore undertook a detailed study of the DSM. The author was able to make several recommendations to the Auto21 project team regarding the team structure, workflow, and general systems design of the Reflex vehicle by the conclusions of that project.

Subsequently, a collaboration was undertaken with a product development firm in the Greater Toronto Area. The company provided a mechanical design problem of current interest to them. The author was able to use the DSM to make recommendations on how the product could be improved. Further details are given below.

Chapter 3 Best Practices

3.1 Introduction

In the field of best practices, work has focused on the areas of health care, manufacturing, and management science. Virtually no work has been done on best practices in product development and engineering design. Notwithstanding this lack of "scientific" literature, the concept of best practices has a definite appeal to the engineering industry because using best practices means better technical and business performance for the engineering industry. The existing literature indicates that there is no single field into which the study of best practices falls.

It seems reasonable to believe that the codification of methods to identify and implement best practices—to develop a proper *body of knowledge* for it—would have definite benefits to industry.

- A designer could quickly and intuitively search for different strategic and tactical methods to solve specific classes of design problems. The designer could access all the information needed to select and implement the practice that is best suited to the designer's needs. The body of knowledge could support the judgements of design engineers in design-related problems by including references to successful applications of best practices.
- It could also help design engineers to improve collaboration and communication in design and development processes by providing a common methodological framework.
- Corporate knowledge could be distributed more easily to new employees due to its presentation in a standardised format.
- Corporate knowledge could be more easily extended by absorbing some of the expertise of retiring employees and by capturing the practices that worked best for them.
- Training times could be decreased due to procedural standardisation and adoption of best practices for training.
- Collaboration and communication between engineers could be improved as best practices become widely adopted in an organisation.

- Development processes could be more integrated and efficient because of standardisation of procedures via best practices.
- Cost, production, quality, scheduling, environmental issues, customer satisfaction, and employee satisfaction could all improve by uniform adoption of practices that are demonstrably superior (i.e., "best").
- Similarly, the time to market could be reduced, improving corporate competitiveness.

Many articles and documents make the case that best practices can improve the health of an organization in terms of cost, production, schedule, quality, safety, environment, customer satisfaction, and employee satisfaction However, there is no universally accepted definition of the term "best practice," and virtually no work indicating how they can be identified and implemented.

For example, appendix A (page 67) contains in its entirety a best practice implemented by Dayton Parts Inc. (DPI), a manufacturing company.

The best practice is described only by a case study. This case study approach to describe best practices is universal in the literature. The case study explains how DPI substantially improved its scheduling of weekend shift work by applying a scheduling technique conventionally used only in hospital settings.

This case study shows the merit of looking for solutions in different industries or sectors but gives no reference or indication as to how one might proceed in such a search, nor does it suggest how DPI found the hospital shift scheduling techniques and proved that it would work. This is typical of best practices reported in the literature. Clearly, this is an open research question in the area of best practices.

The author has found only three operational definitions of the term *best practice* in the literature; these are given below.

> "A best practice is a process, technique, or innovative use of equipment or resources that has a proven record of success in providing significant improvement in cost, schedule, quality, performance, safety, environment or other measurable factors which impact the health of an organization" [1].

> "Best practices are simply the best way to perform a business process. They are the means by which leading companies have achieved top performance, and they serve as goals for other companies striving for excellence" [2].
>
> "A high-performance way of achieving business objectives, which solves problems, creates opportunities, and improves business results" [3].

Based on the reviewed literature, the author has adopted the following working definition of best practice.

> A best practice is a process of innovative use of existing ideas, methods and resources that has a proven record of success in providing significant improvement in organizational performance in terms of cost, production, schedule, quality, safety, environment, customer satisfaction, and employee satisfaction.

Some discussion regarding this definition is presented below. Hereafter, the abbreviation BP is used for best practice.

BPs arise from the qualitative comparison of existing practices. A practice can be purely procedural (e.g., a workflow) or tied to some specific artifact (e.g., the best way to machine some feature in metal using a lathe). They are qualitatively compared because (a) there are no standard scales by which such comparisons can be quantified, and (b) the number of variables that influence the identification of a practice as a BP lead to an intractably complex evaluation.

In order for any practice to be considered a best practice, *its superiority must be demonstrable*. This implies that the identification of best practices involves a qualitative comparison of different existing practices, and practices that achieve the highest standing in a rank order of the ratings are identified as best practices. BPs have proven records of success, meaning that these practices already exist in some facilities. Therefore, all best practices are the most preferred practices because these practices have proven records of success, and all new practices (i.e., innovations) are non-preferred practices because these practices have no proven records of success.

Innovation is not a requirement for BP. One may accumulate a number of small changes in existing practices that cumulatively develop a highly improved state of existing practices at a lower level of corporate risk. On the other hand, innovation (i.e. entirely new practices) implies a dramatic change, which can be destabilizing and carry considerable risk. BPs can cover both these scenarios.

The definition clearly includes technical, business, management, financial, and ethical matters as factors that significantly influence the state of an organization. *A good BP balances all these factors* (technology set up, functional structures, nature and behaviour of supply chain, level of expertise of organization members, etc.) of a given organization and its environment. Furthermore, the discovery of existent BPs and development of new BPs (i.e., innovation) require collaboration between the various specialists (practical knowledge experts) and the stakeholders (all person who risk gain or loss due to a change in practice).

3.2 The literature on Best Practices

The case studies of best practices in the literature are of an extremely specific nature. Most of these best practices are related specifically to maintenance, management, and manufacturing sectors. Due to their specific nature, these best practices cannot be adapted to other sectors.

For example, in appendix A (page 74) there is a case study of a best practice that has been implemented by Nascote.

Nascote, a high production supplier of automobile parts, adopted a Quick Mold Change practice for its tool change process. A team was established to devise and implement the new practice. The team consisted of superintendents, supervisors, technicians, and tool changers from each shift, to get information on how to reduce the time for the tool change process. The team applied an 'As Is' analysis technique. First, team members discussed their role in the tool change process. Next, the team determined and recorded the actual time for the tool change process, identifying all problems encountered during the change process. All these data became a corporate baseline for process improvement.

The team developed a four-day, continuous improvement plan. They met on a regular basis to monitor progress and provide resolution of problems encountered during the improvement process. To better develop a target of improvement, the team benchmarked two companies with a similar product line and mix. Finding the 'As Is' state gave the company the raw data needed to eventually develop a new six-step process instead of the existing 12-step process.

This case study highlights a number of important points.

- Benchmarking other organizations helps to identify best practices and targets for potential improvement.
- The company reduced the 12 steps of its tool change process to 6 steps, but it does not indicate the method used to achieve that reduction.
- Due to the specific nature of this practice, this practice cannot be implemented easily at other companies.

The specific nature of best practices as described by case studies raises a problem, as has been indicated by Reinertsen [4]: it is virtually impossible to transplant a best practice from one organization to another organization or within same organization. This is because of differences in the environment and the culture of organizations, technological setup, functional structures of the organization, nature and behaviour of organization's supply chain, and level of expertise of organizations' members. Also due to these variables, there is no way to assert that a best practice in one organization will also be a best practice in another organization. Therefore, a best practice is a best practice only in the context in which it was determined to be best. Of course, this assumes that specific case studies are the only way to capture BPs. There does exist work that there are other methods to capture BPs that can overcome this problem.

- No mention is made of a methodological framework for implementing BPs.

In light of these points, there is an opportunity for research in the field of BPs to address the shortcomings typified by this case study.

The definitions of BP in the literature do not commit to a level of specificity. The BP need not be as specific as in the case studies (e.g., Quick Mold change practice). On the other hand, BP cannot be as general as general principles of design (e.g., "minimize the number of parts") that are too generic to provide direct guidance to design engineers and design managers.

So there is need of BPs—in between specific BPs and general principles—that are general enough to apply to many applications and yet specific enough to be implemented directly.

Since BPs can be either too specific or too general, some criterion is required to identify BPs that are neither too specific nor too general. So a characterization of BP has the following characteristics.

1. A BP must be *goal oriented*; that is, a BP must have a purpose of implementation.
2. A BP must be *descriptive*; that is, a BP must provide some indication of the kind of artifact that will result from its implementation.
3. A BP must be *generative*; that is, a BP must provide direction as to the kinds of actions to be taken to achieve the goal.
4. A BP must be *broadly applicable*; that is, it must be possible to think of at least three different industrial situations in which the BP would apply.
5. A BP must *not be universal*; that is, it must be possible to think of at least three different industrial situations in which the BP does not apply.

Some explanation on the characteristics 4 and 5 is warranted. The author was looking for practices that are neither too specific nor too general, so there was a need for some way to identify the middle ground that covers the right kind of practices, extendible into some, but not all, other domains. The author has chosen the arbitrary criterion of three different industrial situations. Two situations may be too few; five may be too many. The author is not aware of any other work that treats this issue. Therefore, until the author either finds such research in the literature or devises a better rationale for selecting a criterion, this author will retain the one rule of three instances.

3.3 Identifying Best Practices: Benchmarking

In the field of best practices, a key issue is the identification of best practices. By reviewing the literature, the author has found only one widely used method for identifying BPs: benchmarking.

The following definitions of benchmarking were obtained from reviewing the literature [5-12].

> "Benchmarking is a performance measurement tool used in conjunction with improvement initiatives; it measures comparative operating performance of companies and identifies the best practices" [5].
>
> "Benchmarking is the continuous process of measuring products, services, and practices against the toughest competitors or those companies recognized as industry leaders" [6].
>
> "Benchmarking is a systemic and continuous measurement process; a process of continuous measuring and comparing an organization's business processes against business leaders anywhere in the world to gain information that will help the organization take action to improve its performance"[7].
>
> "Benchmarking is a continuous search for and application of significant better practices that leads to superior competitive performance" [7].
>
> "A continuous, systematic process for evaluating the products, services, and work processes of organizations that are recognized as representing best practices for the purpose of organizational improvement" [8].

Based on the existing reviewed literature, the author has adopted the following working definition of benchmarking.

> Benchmarking is a systematic, continuous improvement process involving the measurement of products, processes, organizational structures, and operations to identify best practices for the sake of significantly improving corporate performance.

Benchmarking is a tool to identify best practices through the assessment of different practices from different organizations and then rating these practices against various criteria. Those practices that are at the top of the rank order are identified as *best* practices. In the benchmarking process, different groups of organizations from different sectors are involved in order to maintain the security of process-related matters. Also, they can share their practical knowledge without any fear of releasing information about their internal processes. For example, the engineers from the automotive industry have practical knowledge of automotive sectors, but they do not have any practical knowledge related to the chemical industry. Similarly, engineers from the chemical industry have practical knowledge of the chemical industry, but they do not have any practical knowledge related to the automotive industry. Since these engineers have different industrial experiences and exposure to different practices, these engineers can share their practical knowledge without any risk of releasing information about their internal processes. This kind of benchmarking has come to known as *external benchmarking*.

In the *internal benchmarking* process, different groups within the same organization share their practical knowledge. For example, in an automotive company the engineers of the machining division share their practical knowledge with the engineers of the engine assembly division.

Because of the sensitive nature of benchmarking and the danger of releasing sensitive information about an organisation's internal processes, there is little "scientific" literature on what criteria are used to rank practices or how these exercises are best conducted.

Virtually all of the existing work on benchmarking has come from the field of management science. Because of this, the BPs so identified would focus on business management issues rather than on actual design practice. Therefore, if we were interested in looking at best practices as a means of improving the technical act of design engineering, it would be difficult to derive any benefit from those criteria, even if we knew exactly what they were.

One critical issue in which further work is required, then, is the identification of a list of fundamental criteria that can satisfy any best practice for design. A more detailed discussion of benchmarking is beyond the scope of this thesis.

3.4 Implementing Best Practices: The matrix of change (MoC)

A second key aspect in the field of BPs is the matter of implementation. Based on the reviewed literature, the author has found only one tool used for implementation of BPs: The Matrix of Change (MoC) [13, 14]. This technique was developed by Brynjolfsson, Renshaw and van Alstyne at the Sloane Business School at MIT to assist managers in developing implementation strategies for changing old or existing practices and adopting new practices (not necessarily best practices).

It is a management tool that can help managers in issues such as the implementation of change, stability of change, process sequence of change, location of change, pace of change, and stakeholder (all persons who risk gain or loss with respect to new change) interests.

The MoC is quite similar to the House of Quality [15] in form, a convenience for its introduction into organizations. It indicates the interaction between existing practices and new practices. This technique allows the Change Management team to study the effect of new practices on the system and also assist the allocation of resources for an efficient and effective transition between old practices and new ones.

The MoC system consists of three matrices (1) the collection of existing practices, (2) the collection of target practices (desired practices), and (3) a transitional state that provides bridges between existing practices to target practices and a set of stakeholders' evaluation (i.e. the feed back from stake holders on proposed changes)

3.5 Summary

The following conclusions are based on the literature reviewed.

The field of best practices (BPs) is not established or even well organized. More work is required to develop and establish this field as a scientific and engineering field.

Benchmarking is only one widely used tool for the identification of best practices, and more work is required to develop reliable methods for benchmarking in terms of technical applications rather than management applications.

As shown in Appendix B, most case studies of best practices relate to management applications. Benchmarking is only one tool used for the identification of these best practices. More work is required to develop a more reliable and standardized set of criteria and methods for benchmarking within technical domains (rather than management domains).

The Matrix of change is only one well-documented tool for the implementation of new practices.

The author's contributions with regard to best practices are:

(a) synthesis of an operational definition of the term suitable for application in engineering;
(b) identification of key properties of best practices, which form the core of a body of knowledge on this topic;
(c) identification of benchmarking and the Matrix of Change as the two fundamental quantitative tools that can be used to work with best practices in engineering.

Chapter 4 Design Structure Modelling

As part of the Reflex project (see Chapter 2), there was a need to develop a framework for the collaboration of non-collocated student teams and to develop innovative new vehicle systems. Students from different universities with different technical backgrounds were involved in the Reflex project. It was important that everyone was kept informed of design decisions to avoid conflicts. There was, therefore, a need to set up a proper communication and project management structure to coordinate the students, to support good team work, to develop collaboration between Reflex students, and to develop and modularize the system level design of the project.

A number of tools were studied for this purpose; the only tool that was found suitable was the design structure matrix (DSM).

This section presents an overview of the tools that were considered, their evaluation, and the reasoning for selecting the DSM.

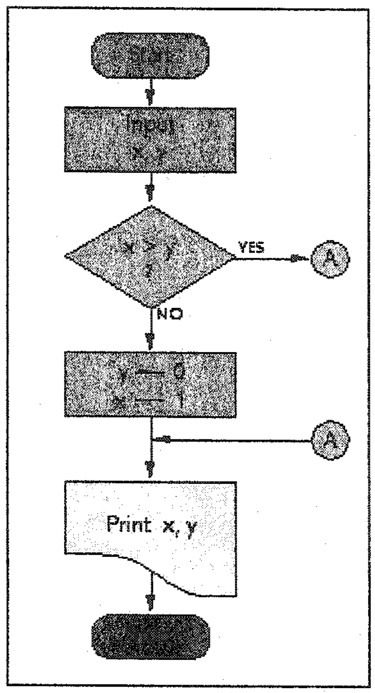
4.1 Modelling Tools

In this section, a number of modelling tools are reviewed with respect to their applicability to the design modelling of non-geometric information in general, and to the Reflex project in particular.

There was, therefore, a need for an appropriate tool that could fulfil the requirements of the Reflex project by supporting the following general requirements: (a) physical systems modelling, (b) dependent task planning, (c) treating task interdependency, (d) project management and scheduling, (e) resource allocation, and (e) proper coordination and communication between students. For each tool, the relative merits and problems (pros and cons) are given.

4.1.1 Flowchart

A flow chart is a graphical representation of a process or system in which different symbols (square, circle, etc.) are used to represent the different activities; arrows represent the direction of flow of the process [21, 22].



flowchart

Figure 4.1: Sample flow chart of a process [21]

Pros

- Flow charts are simple diagrams that describe tasks and the order in which they occur, their inputs and outputs, and decisions that must be made during and between tasks.
- Flow charts are classically used in computer science but have been successfully used to describe many engineering management, and other, processes such as assembly processes and manufacturing processes.

Cons

- Flow charts do not show dependency between tasks.
- Flow charts cannot be used for project scheduling because no time data is available.
- Flow charts cannot show the structure of entities or be used in physical systems modelling.

4.1.2 Gantt chart

A Gantt chart is a horizontal bar chart that graphically represents the relationship between time and different tasks or activities of systems or projects [21, 23].

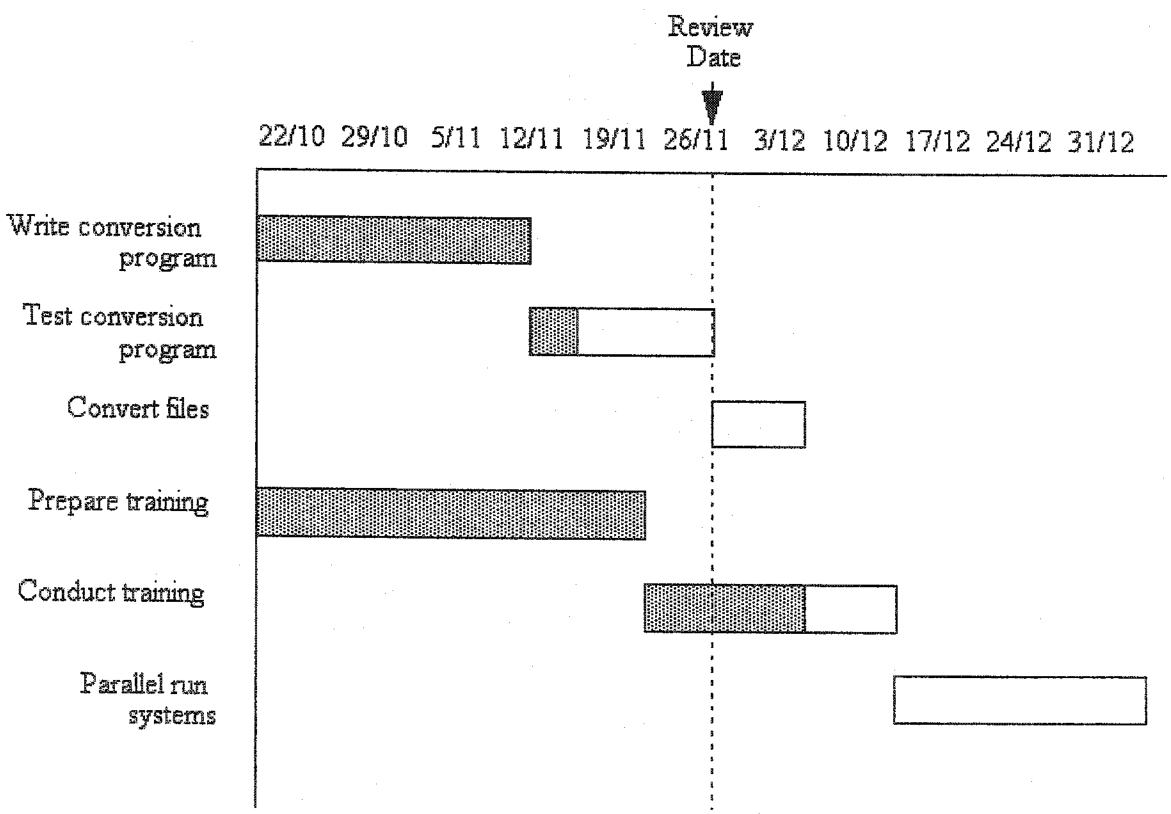


Figure 4.2: Gantt chart of a Project [21]

In figure 4.2, the horizontal axis represents the time period (start and end times) of different tasks, and the vertical axis represents the different tasks of the project. Darkened bars indicate completed tasks or portions of tasks that have been completed. A vertical line indicates a review date [21, 23].

Pros

- Time data is available on a Gantt chart.
- A Gantt chart is a good project-planning tool, in contrast to a flow chart.
- As a graphical scheduling technique, a Gantt chart is simple to develop, use and understand, and it can show many aspects of tasks and resources clearly.
- Actual completion times can be compared with planned times in Gantt chart.
- A Gantt chart is an efficient technique for projects with few dependencies and routine work activities.
- Gantt charts emphasizes time rather than task relationships.

Cons

- Gantt charts cannot show interdependency among activities.
- There are no branches as in a flow chart.
- Gantt charts are difficult to use for project tracking without computer support.

4.1.3 PERT (Program Evaluation and Review Technique)

PERT (Program Evaluation and Review Technique) is a project management technique used to schedule, organize, and coordinate different tasks of projects, processes, and systems [24, 25].

A PERT chart is a graphical representation in which arcs represent different tasks, arrows represent activities, and dashed arrows represent "dummy activities" [24,25]. In figure 4.3, the tasks 1, 2, 4, 8, 10 are dependent on each other, and these tasks must be completed sequentially.The tasks between 1 & 2 and 1 & 3 are parallel and are not dependent on each other.

Figure 4.3 shows there is no activity between nodes 6 and 9, but the activity 9 cannot be started until activity 6 is completed. Consequently, a "dummy activity" is used to connect nodes 6 and 9, and this "dummy activity" has zero duration.

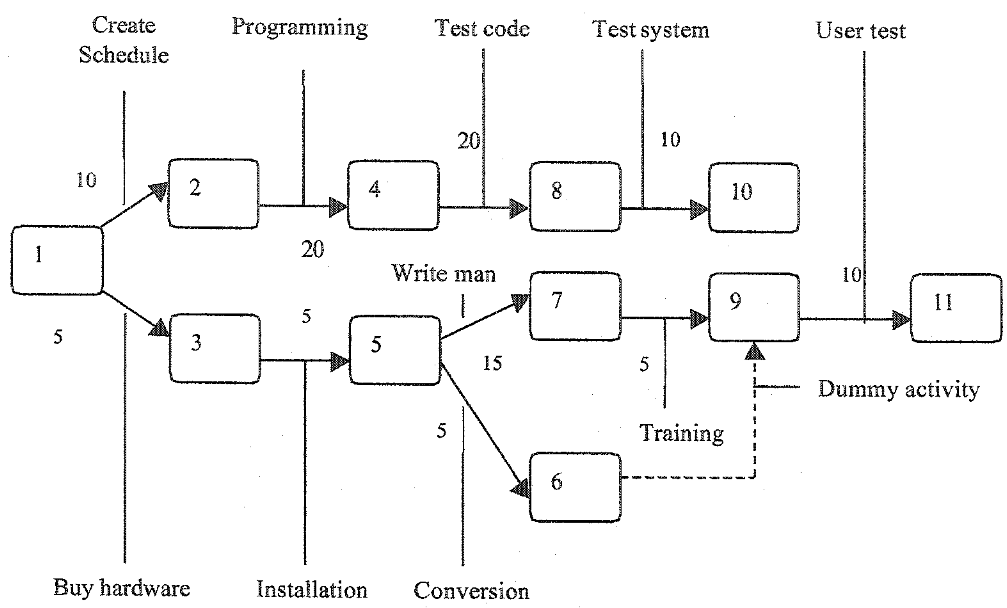


Figure 4.3: PERT Chart of a system [24]

Pros

- The order of activities can be shown, like flow charts but unlike Gantt charts.
- In contrast to Gantt charts, PERT is a good for project scheduling in large projects because it shows interdependency among activities easily.
- PERT charts concentrate on the relationships among tasks (especially their dependencies) rather than on time only, as is the case for Gantt charts.

Cons

- Like Gantt charts, PERT charts are difficult to use for project tracking without computer support.
- PERT charts are difficult to analyse without computer support.
- PERT charts do not show interdependency among activities graphically.

4.1.4 CPM (Critical Path Method)

CPM is a project management tool used to analyze, schedule, and evaluate a project from start to finish with a step-by-step analysis of the sequences and timing of all the activities and operations in the project [24, 25].

CPM indicates the critical paths, which is the longest path in a project and consists of tasks and activities. Activities are shown by a double line. For example, in figure 4.4, activities A, B, D, and E depend on each other. The time duration for these activities is 14 days, which is the maximum time, so the critical path is between A-B-D-E. CPM is very similar to PERT and is sometimes called PERT/CPM [24, 25].

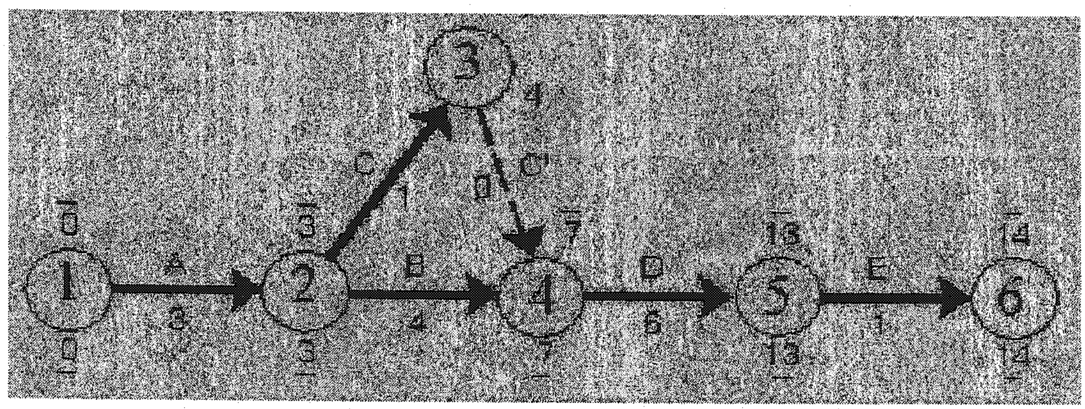


Figure 4.4: Sample CPM Chart of a Project [24]

The CPM chart is a graphical representation in which circles represent events, arrows represent activities (name of activity above the arrow and duration of activity below the arrow), and dashed arrows represent "dummy activities" [24, 25]. Figure 4.4 shows that activity A must be completed before activity B or C can begin. Activity B and C are parallel and not depend on each other. The "dummy activity" has zero duration and is used to connect two nodes. "Dummy activity" C indicates that activity D cannot be started until activities B and C are completed. Also, activity D must be completed before activity E can begin.

Pros

- CPM is better than PERT because it highlights the critical path.
- Like PERT, CPM shows interrelationships among activities.
- CPM provides a graphical view of the entire project with completion dates and support activities for every stage of project, in contrast to Gantt charts, Flow charts, and PERT.

Cons

- CPM is more complex to draw and understand than Gantt charts and PERT.
- Like Gantt and PERT, CPM is difficult to draw manually for large and complex projects.
- CPM can show parallel branches but not decision (Boolean or) branches.

4.1.5 Arrow diagram method (ADM)

The arrow diagram is a network diagramming tool also called an Activity On Arrow (AOA) diagram [26, 27]. In this method, arrows represent activities. Arrow tails represents the start and arrow heads represents the end of the activity. Activities are connected with nodes and nodes represent the starting and ending points of activities [26, 27].

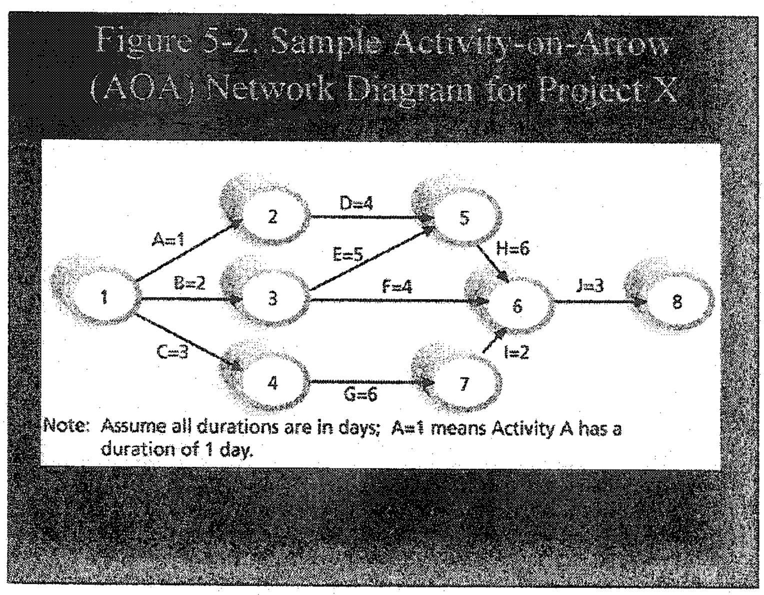


Figure 4.5: Sample Arrow network diagram of a project [27].

Pros

- Arrow networks are quicker and faster to draw and easier to understand than CPM.

Cons

- ADM can only show finish to start dependencies.

4.1.6 Precedence Diagram Method (PDM)

The precedence diagram method is a network diagramming technique, in which nodes represent the activities and arrows show their sequencing [26, 27].

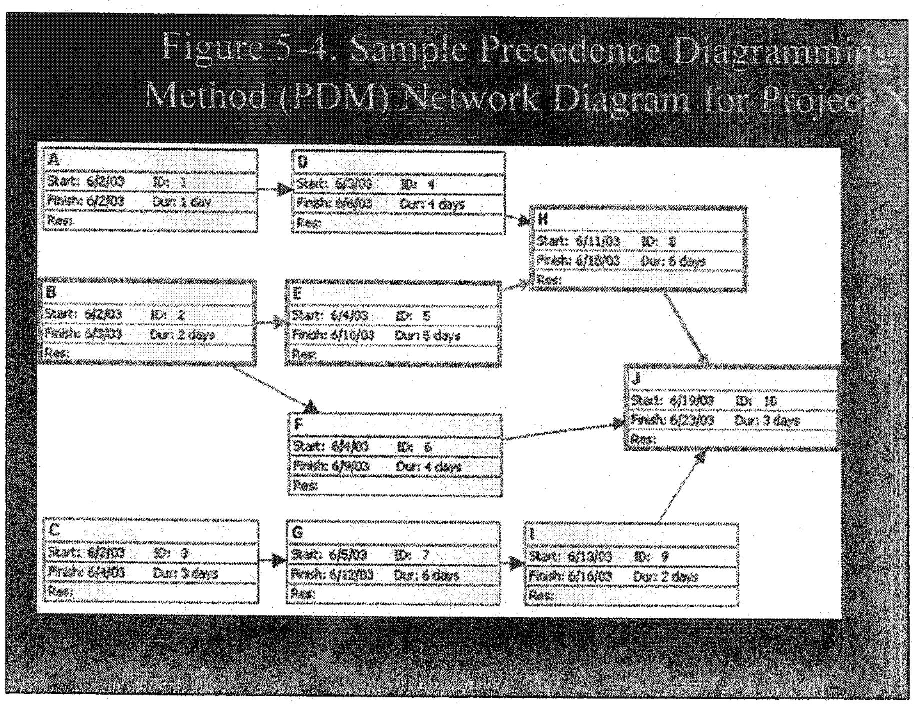


Figure 4.6: Sample Precedence network diagram of a project [27].

Pros

- PDM can represent interdependency between activities like PERT and CPM.

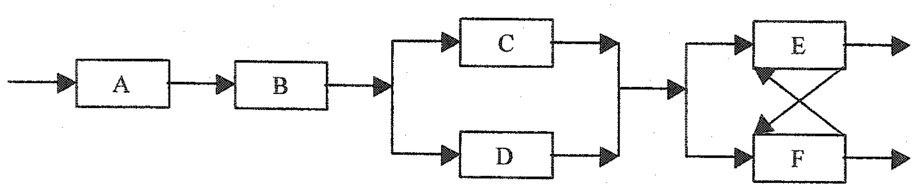
Cons

- Large and complex projects are difficult to draw manually like PERT and CPM.

The final tool investigated was the design structure matrix (DSM). This is a matrix-based tool that facilitates a wide number of engineering tasks, covering both project management aspects as well as actual product development issues. Since the author selected DSM as the appropriate tool for the Reflex project, the DSM is described in detail below.

4.2 The Design Structure Matrix

The DSM is a matrix-based tool that is used to manage interactions among entities. The entities can be features in a part, parts in an assembly, components in a system, engineers in a team, or tasks in a process. It has been successfully used to modularize products and assemblies, organize teams, and manage projects and systems. The DSM was invented by Steward and has since been extensively developed the Massachusetts Institute of Technology. The use of the DSM was described by Steward in the 1980's (Browning 1998, Ulrich 2000) for the analysis of the structure of a system design. Eppinger, Whitney, Smith and Gebala (1994) provide an overview of the basic DSM described by Steward to represent the dependency of tasks on one another.



	A	B	C	D	E	F
A	A					
B	X	B				
C		X	C			
D		X		D		
E			X	X	E	X
F			X	X	X	F

Figure 4.7: Simplified example of a Task DSM [28]

In the sequence of tasks in figure 4.7, tasks A and B are in series, C and D are in parallel, and E and F are coupled. In the DSM, tasks in the columns and rows are identically labeled. The information supplies from column elements to row elements. Since A and B are in series, task B requires information from task A. Parallel tasks C and D require information only from task B. The coupled tasks E and F require information from tasks C and D as well as each other. The X marks below the diagonal show that information is fed forward to later tasks and the X mark above the diagonal indicates that information from task F must be fed backward to task E before its completion. Such marks indicate occurrences of feedback in the system.

Typically, a DSM is a square matrix. Each row and column stands for one entity. Each cell represents the interaction of the entities indicated by the cell's row and column. The diagonal elements represent dependencies of an entity on itself, and are usually blank or marked with the task identification.

Relationships are directed from columns to rows. For example, in the figure above, task A provides input to task B—i.e., task B depends on task A. Reading across a row gives a list of all entities feeding information into the entity represented by the row. Reading down a column gives a list of all entities accepting information from the entity represented by the column. Columns and rows can be rearranged to reveal relationships among all the entities that would otherwise remain hidden in the matrix.

There are a number of operations that can be performed on a DSM, implying changes to the entity (product, process, or organization) represented.

4.2.1 DSM Partitioning

Partitioning is the process of re-ordering the DSM rows and columns to eliminate the feedback marks above the diagonal of matrix, resulting in the lower triangular form of matrix because feedback marks will cause design iteration in the development process [29-34].

There are several algorithms for DSM partitioning. However, they all are similar with a difference in how do they identify loops of information. All partitioning algorithms included following steps [29].

- Identify system elements (or tasks) that can be determined without input from the rest of the elements can easily be identified by observing an empty row in the DSM. Place those elements in the top of the DSM. Once an element is rearranged, it is removed with its corresponding marks from the DSM and this step is repeated on the remaining elements.
- Identify system elements that deliver no information to other elements in the matrix. Those elements can easily be identified by observing an empty column in the DSM. Place those elements in the bottom of the DSM. Once an element is rearranged, it is removed from the DSM with its corresponding marks and this step is repeated on the remaining elements.
- After this if there are no remaining elements in the DSM, then the matrix is complete partitioned.

For example, figure 4.8 shows the parameter-based DSM for robot arm design activities with feedback marks above the DSM diagonal.

The figure shows that the parameters are not in sequence. For example, I depends on A, A depends on E, and E depends on F. So in order to find I, one must first find parameters F, E, and A. This makes the process complex, increases design iterations, communication, and negotiation, increases lead-time, and slows development.

Parameters		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Housing outer radius	A	.				X										
Housing inner length	B		.													
Housing outer radius, shaft	C			.												
Housing wall thickness	D			X	.	X										X
Housing inner height	E					.	X									
Arm: y-coordinate, inner fixation screw	F						.									
Arm: width pocket for support bearing	G							.	X						X	
Arm:distance from shaft five to support bearing	H								.						X	
Arm: radius pocket for support bearing	I	X								.		X	X	X		X
Arm:radius pocket for pinion bearing	J										.					
Arm:x coordinate inner fixation screw	K											.				
Arm: y-coordinate, outer fixation screw	L												.			
Arm:x coordinate outer fixation screw	M													.		
Arm:distance shaft five to housing back flange	N		X												.	
Arm:radius shaft seat	O			X												.

Figure 4.8: Parameter-based DSM for robot arm design activities (adapted from [34]).

- Figure 4.9 shows the partitioned DSM with no feedback mark above the diagonal.

Parameters		F	B	N	E	C	O	M	L	K	H	A	J	I	G	D
Arm: y-coordinate, inner fixation screw	F	.														
Housing inner length	B	X	.													
Arm:distance shaft five to housing back flange	N		X	.												
Housing inner height	E				.											
Housing outer radius, shaft	C					.										
Arm:radius shaft seat	O					X	.									
Arm:x cordinate outer fixation screw	M							.								
Arm: y-coordinate, outer fixation screw	L								.							
Arm:x cordinate inner fixation screw	K									.						
Arm:distance from shaft five to support bearing	H			X							.					
Housing outer radius	A				X							.				
Arm:radius pocket for pinion bearing	J												.			
Arm: radius pocket for support bearing	I						X	X	X	X		X		.		
Arm: width pocket for support bearing	G			X							X				.	
Housing wall thickness	D				X	X	X									.

Figure 4.9: Partitioned DSM (adapted from [34]).

Figure 4.9 shows that all the parameters are in sequence. For example, parameter B depends on parameter F and N depends on B, but N has no dependency with F. So in order to find B, F is required, and to find N, B is required, so there is no interdependency among parameters. This makes the process simple, reduces extra communication and negotiation, reduces design iterations, and reduces lead-time, resulting in a better product with a faster development process.

For complex engineering systems, it is difficult to eliminate the feedback marks or get a lower triangular form of the matrix by simply re-ordering the DSM rows and columns because of the interdependencies between tasks (coupled tasks), as shown in figure 4.10. In this scenario, the goal of partitioning constitutes a change—from eliminating the feedback marks above the diagonal of matrix to moving them as close as possible to the diagonal of the matrix in block form, as shown in figure 4.11 [29].

4.2.1.1 Clustering

Clustering is the process of identifying the modules or teams from DSM (component based or team based) elements that interact with or depend on each other [29-34].

For example, consider a component-based DSM for automotive engine components, as shown in Figure 4.10.

Components		A	B	C	D	E	F	G	H	I
Fly wheel	A	•					X	X		
Fuel injector	B		•			X				X
Cam shaft	C	X		•	X		X			
Timing Gears	D			X	•		X			
Exhaust Manifold	E		X			•			X	X
Crank shaft	F	X		X	X		•	X		
Crank Pully	G	X						•		
Main Bearing	H						X		•	
Intake manifold	I		X			X				•

Figure 4.10: Component-based DSM showing materials interactions for automotive engine components

It is easier for design engineers to interact in smaller teams, rather than larger ones. Also, the difficulty of managing a development team increases with the number of team members.

For example, consider Figure 4.10. There is one big chunk. In this chunk, the component A design engineer has interaction with *only* the designers of components C, F, and G. However, the component A design engineer is forced to interact with other component design engineers because they are on the same team as shown in the Figure.

In this way, more design engineers are involved in the development process, making the process more complex, requiring extra communication and negotiation, consuming more time, yielding less productive and parallel work, and making decision processes difficult, resulting in a slower development process.

Now consider Figure 4.11. There are 3 smaller chunks. Chunk 1 design engineers will not exchange information with chunk 2 design engineers. Similarly chunk 2 design engineers will not exchange information with chunk 3 design engineers, except for the component F design engineer, because that engineer is a member of both chunks 2 and 3.

In Figure 4.11, small chunk arrangement makes the process simple, reduces extra communication and negotiation, makes decision process easy, consumes less time, and constitutes more parallel and productive work, resulting in better product with a faster development process.

Small chunks reduce iteration cycle time, compared to large ones. For example in Figure 4.11, there are 3 small chunks; each chunk has its own design iteration loop. The design engineers of chunk 1 will not be involved in the design iteration loop of chunk 2 Similarly chunk 2 design engineers will not be involved in the iteration loop of chunk 3, except for design engineer F because design engineer F is a member of both chunks 2 and 3. In this way, fewer design engineers will be involved in each chunk iteration loop, reducing the design iteration cycle time of each chunk and resulting in a faster development process. For small design problems, one can assign one designer to each chunk, increasing the independence of the designers.

Components		I	E	B	C	D	F	A	G	H
Intake Manifold	I	.	X	X						
Exhaust Manifold	E	X	.	X	Chunk 1					
Fuel Injector	B	X	X	.						
Cam shaft	C				.	X	X			
Timing Gears	D		Chunk 2		X	.	X			
Crank shaft	F				X	X	.	X	X	X
Fly wheel	A						X	.		X
Crank Pully	G				Chunk 3		X	X	.	X
Main Bearing	H						X	X	X	.

Figure 4.11: Clustering of materials interactions in Component-based DSM of automotive engine components

4.2.1.2 Tearing

Tearing is the process of removing the feedback marks from the blocks of the matrix, resulting in the lower triangular form of the matrix. The marks that are removed are called *tears* [29-34].

For example, Figure 4.12 shows a DSM of two variables, A and B. A mark in row A column B means that in order to determine variable A, a value of variable B is first known or assumed, but variable B cannot be determined unless the value of variable A is known or assumed. This interdependency between variables makes a circuit. So a guess or estimate has to be made to break these circuits in design iteration processes.

	A	B
A	.	X
B	X	.

Figure 4.12 Sample DSM of variables.

Steward (1981) suggested the use of level numbers instead of "X" marks. The feedback marks are assigned numerical values, and these numerical values (level numbers) reflect the order in which the feed back marks should be torn. Normally, numerical values range from 1 to 9, depending on the engineer's judgment [29].

For example, level number 9 is less critical (shows low dependency or low interaction), so it will be torn first, and the matrix is re-ordered again. Level number 1 is more critical (shows high dependency or high interaction), so it will be torn later. This process is repeated until all feedback marks disappear, resulting in a lower triangular form of the matrix [29].

Figure 4.13 shows a sample DSM of tasks.

	A	B	C	D	E	F
A	.	0		0		
B		.	0			
C			.			
D				.	0	
E	0		0	0	.	0
F			0			.

Figure 4.13: Task DSM before partitioning

Figure 4.13 shows in the first row that task A depends on tasks B and D. In second row, task B depends on task C. The third row shows that task C does not depend on any task, and so on.

	C	B	F	A	D	E
C	.					
B	0	.				
F	0		.			
A		0		.	0	
D					.	0
E	0		0	0	0	.

Figure 4.14: Task DSM after partitioning

The task C does not depend on any task, so it can be done first. Figure 4.14 shows that tasks B, F, and E depend on task C, so these tasks can be done in parallel. Figure 4.14 shows that tasks A, D, and E depend on each other. This interdependency among tasks makes a circuit, so there is no place to start an iteration within the block. Figure 4.15 shows that the feedback mark between task E and D is assigned a numerical value of 9 in order to tear it and break the circuit.

	C	B	F	A	D	E
C	.					
B	0	.				
F	0		.			
A		0		.	0	
D					.	9
E	0		0	0	0	.

Figure 4.15: Partitioned DSM with Tear mark

Figure 4.16 shows the repartitioned matrix with a torn block. The only mark above the diagonal is within the block, and that will be torn. Since there are no 0 (i.e. critical) marks above the diagonal within block, there are no feedback marks above the diagonal, resulting in a lower triangular form of the matrix.

	C	B	F	D	A	E
C	.					
B	0	.				
F	0		.			
D				.		9
A		0		0	.	
E	0		0	0	0	.

Figure 4.16: Repartitioned with Tear

4.3 Summary

A number of tools were studied for the Reflex project, but not all of these tools were suitable for the Reflex project requirements. The Design Structure Matrix tool is the most flexible and practical tool for the purpose of this work. The DSM tool provides the proper communication and project management structure, and can modularize the systems level design of products.

Chapter 5 Using the Design Structure Matrix in Design

In this chapter, the author will apply the DSM to three "real" applications in automotive engineering. In each case, recommendations on how the specific subject of study can be improved will be based on DSM analysis. Other researchers have applied the DSM to automotive applications, including climate control systems [29], engine design, product development teams [29], brake systems [35], diagnostic system calibration [36], and overall automotive design processes [37]. However, the author has found a novel feature of DSMs that has not been reported in the literature that was reviewed with respect to this method.

5.1 The DSM and the Reflex Project

The DSM was applied to two problems as part of the Reflex project: (1) management of the overall project and the student teams involved, and (2) the overall systems design of the Reflex vehicle power train. The Hybrid vehicle power train configuration is shown in figure 5.1.

The author discussed the design objectives of the project with the Reflex project leader to understand the vehicle power train configuration, the functions of its parts, and the dependency strengths (with respect to physical interface, energy interface, and information interface) among the vehicle power train components.

The criteria used for dependency strength ("strong" and "weak") depend primarily on fail-safe Hybrid vehicle drive conditions as suggested by the Reflex project leader. That is, interactions that were deemed of primary importance to the fail-safe operation of the vehicle power train are termed "strong" (represented by a value of 2 in DSMs), and other, less important interactions are termed "weak" (represented by a value of 1 in DSMs).

For example, if the internal combustion engine fails under highway conditions, the vehicle can drive on electrical battery power to reach a safe destination, so the internal combustion engine has weak dependency strength with other components, whereas the battery has strong dependency strength.

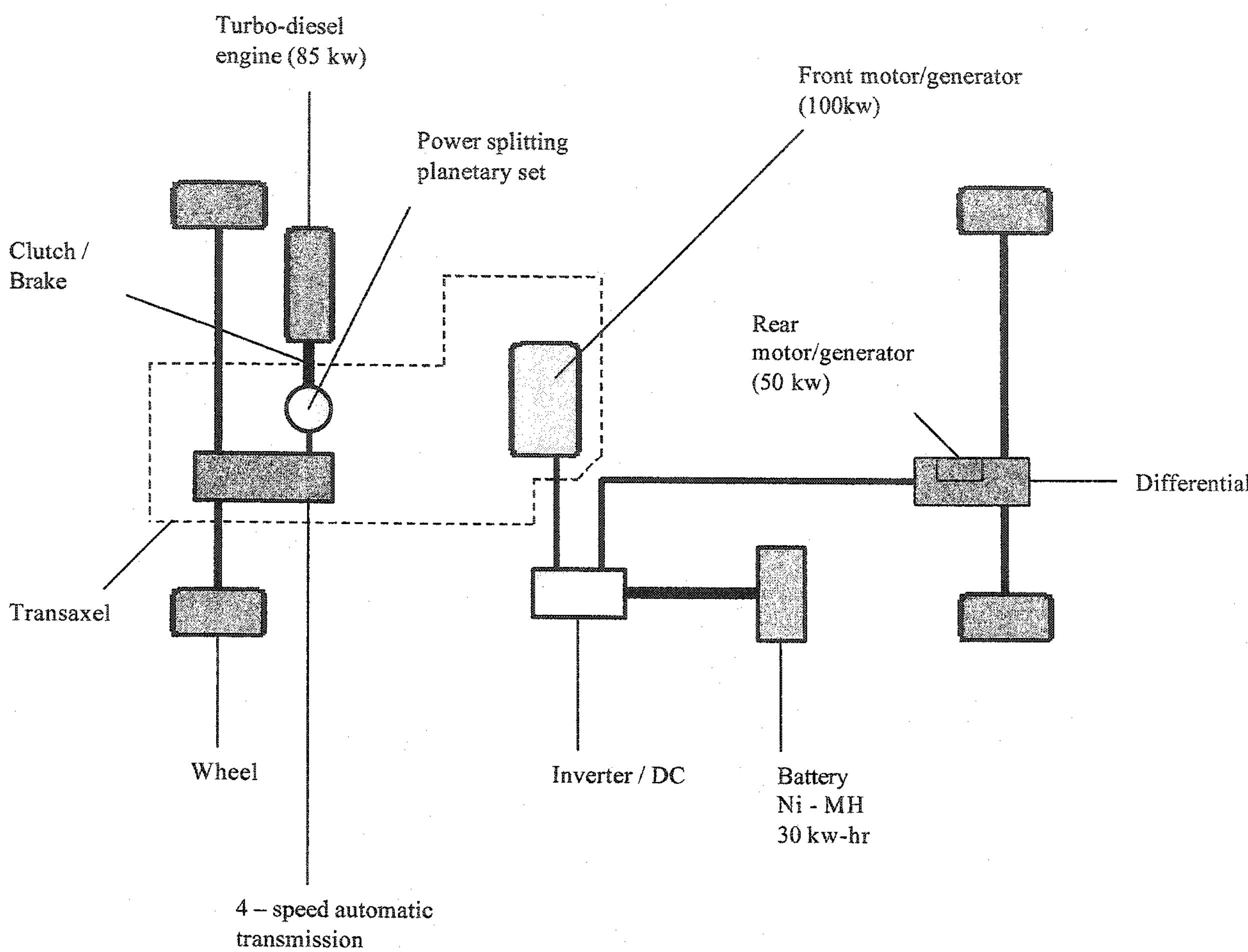


Figure 5.1: Hybrid vehicle power train configuration adapted from [38]

5.1.1 Reflex case 1 (system level design)

Three kinds of interactions were studied for the systems level design of the Reflex power train: the physical interactions (connections of assemblies and parts), the energy interactions (how mechanical and electrical power is transmitted through the system), and information interactions (how the power train is controlled).

5.1.1.1 Physical interface of vehicle power train components

The author constructed a physical interface DSM of the Reflex power train components as shown in figure 5.2 and applied standard operations to that DSM to create clusters of highly physical interacting components as shown in figure 5.3. These DSMs show the strength (importance) of the physical connections between assemblies and parts.

Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Front wheels	A	.	2	2	2	1	2					2				2
Transmission	B	2	.	2	2	1	2					2				2
Planetary power splitter	C	2	2	.	2	1	2					2				2
Clutch/brake	D	2	1	1	.	1	2					1				1
Internal Combustion Engine	E	1	1	1	1	.	1					1			2	1
Front motor/Generator	F	2	2	2	2	1	.					2				2
Invertor	G							.								
Battery	H								.							
Rear motor/Generator	I									.	2		2	2		2
Rear Differential	J									2	.		2	2		2
Front axle	K	2	2	2	2	1	2					.				2
Rear axle	L									2	2		.	2		2
Rear wheels	M									2	2		2	.		2
Fuel delivery/storage	N					2									.	
Chassis	O	2	2	2	2	1	2			2	2	2	2	2		.

Figure 5.2: Component-based DSM showing physical interface of vehicle power train components

Figure 5.2 shows the vehicle power train parts identified by name in column 1. Each component is given an abbreviation, appearing in column 2 and row 1. Cells in the body of the DSM show the strength of physical interaction between different components. Components do not "interact" with themselves, so the diagonal is empty. Components that physically interact with one another strongly have "2" in the corresponding cell. Other components that interact more weakly have a "1" in the corresponding cell. Components that do not interact, or that interact very weakly, have blank cells.

It is easier for design engineers to interact in smaller teams than larger ones, and the difficulty of managing a team increases exponentially with the number of team members.

For example, consider Figure 5.2. There is one big chunk. In this chunk, component G and H design engineers have no interaction with other components design engineers, but they have to interact with other components design engineers because they are in the same chunk. In this way, more design engineers will be involved in the development process, making the process more complex, requiring extra communication and negotiation, consuming more time, yielding less productive work, and making the decision process difficult, thereby resulting in a slower development process.

The big chunk in Figure 5.2 has one large iteration loop. Component G and H design engineers have no interaction with other components design engineers, but they have to be involved in the iteration loop because they are in the same chunk. In this way, more design engineers will be involved in the iteration loop, increasing the design iteration cycle time of each chunk and resulting in a slower development process.

Now consider Figure 5.3. This is the same DSM as in Figure 5.2, but having been properly partitioned. In this figure, there are three small chunks. Chunk 1 design engineers will not exchange information with chunk 2 design engineers except for component O design engineer because component O design engineer is a member of both chunks 1 and 2. Small chunk arrangements reduce iteration cycle time, in contrast to large chunks.

Similarly chunk 2 design engineers will not exchange information with chunk 3 design engineers, except for component E design engineer because component E design engineer is a member of both chunks 2 and 3. In this way, fewer design engineers will be involved in the development process, making the development process simpler, reducing extra communication and negotiation, consuming less time, yielding more productive work, making decisions easier, thereby resulting in a better product with a faster development process.

Components		G	H	M	L	J	I	O	F	C	B	K	A	D	E	N
Inverter	G	.														
Battery	H		.													
Rear wheels	M			.	2	2	2	2								
Rear axle	L			2	.	2	2	2								
Rear differential	J			2	2	.		2								
Rear motor/Generator	I			2	2	2	.	2								
Chassis	O			2	2	2	2	.	2	2	2	2	2	2	1	
Front motor/Generator	F							2	.	2	2	2	2	2	1	
Planetary power splitter	C							2	2	.	2	2	2	2	1	
Transmission	B							2	2	2	.	2	2	2	1	
Front axle	K							2	2	2	2	.	2	2	1	
Front wheels	A							2	2	2	2	2	.	2	1	
Clutch/brake	D							2	2	2	2	2	2	.	1	
Internal Combustion Engine	E							1	1	1	1	1	1	1	.	2
Fuel delivery storage	N														2	.

Figure 5.3: Clustering of physical interface in Component-based DSM of vehicle power train

Figure 5.3 shows that components O and E are systems interface components. The design engineers of components O and E are systems integration engineers because components O and E design engineers have shared responsibilities. This means that the people required for these positions must have experience in systems integration and that their job description ought to include systems. Particularly for Reflex, this could mean having professors with systems (or similar) backgrounds supervising student engineers O and E. Other engineers in that figure do not necessarily need a systems integration background. One might even suggest assigning those systems integration components to people at the University of Waterloo (one of the participating Universities), since they have a unique systems engineering program.

The design iteration process of Figure 5.3 suggests that chunk 2 will perform the iteration cycle first and then freeze the iteration process and will give the result of iteration to chunks 1 and 3 through design engineers O and E. Then chunk 1 and 3 will perform their iteration cycles and freeze the iteration cycle and will give the iteration results to chunk 2 through design engineers O and E and repeat the procedure. It might also be possible to synchronise the iteration cycles of the chunks so that they can be parallelised, further shortening development times.

5.1.1.2 Energy interface of vehicle power train components

In a manner similar to that in the preceding section, the author constructed an energy interface DSM of the vehicle power train components (Figure 5.4) to show the strength importance of the energy interactions between the components.

Components		A	B	C	D	E	F	G	H	I	J	K	L	M
Front wheels	A	.	2	2	2	1	2	2	2			2		
Transmission	B	2	.	2		1	2	2	2			2		
Planetary power splitter	C	2	2	.		1	2	2	2			2		
Clutch/brake	D	2			.									
Internal Combustion Engine	E	1	1	1		.	1	1	1			1		
Front motor/Generator	F	2	2	2		1	.	2	2			2		
Invertor	G	2	2	2		1	2	.	2	2	2	2	2	2
Battery	H	2	2	2		1	2	2	.	2	2	2	2	2
Rear motor/Generator	I							2	2	.	2		2	2
Rear Differential	J							2	2	2	.		2	2
Front axle	K	2	2	2		1	2	2	2			.		
Rear axle	L							2	2	2	2		.	2
Rear wheels	M							2	2	2	2		2	.

Figure 5.4: Component-based DSM showing energy interface of vehicle power train components

In Figure 5.4, the component A design engineer has an energy interface with components B, C, D, E, F, G, H, and K, but no energy interface with components I, J, L, and

M. Still, the component A design engineer has to interact with components I, J, L, and M because they are in the same chunk. As in the preceding section, this is found to be highly inefficient.

Now consider Figure 5.5. As was found with Figure 5.3, we now have a more efficient process because there are three smaller chunks instead of one large chunk.

Components		M	L	J	I	G	H	F	C	B	K	E	A	D
Rear wheels	M	.	2	2	2	2	2							
Rear axle	L	2	.	2	2	2	2							
Rear differential	J	2	2	.	2	2	2							
Rear motor/Generator	I	2	2	2	.	2	2							
Invertor	G	2	2	2	2	.	2	2	2	2	2	1	2	
Battery	H	2	2	2	2	2	.	2	2	2	2	1	2	
Front motor/Generator	F					2	2	.	2	2	2	1	2	
Planetary power splitter	C					2	2	2	.	2	2	1	2	
Transmission	B					2	2	2	2	.	2	1	2	
Front axle	K					2	2	2	2	2	.	1		
Internal Combustion Engine	E					1	1	1	1	1	1	.	1	
Front wheels	A					2	2	2	2	2	2	1	.	2
Clutch/brake	D												2	.

Figure 5.5: Clustering of energy interface in component-based DSM of vehicle power train

5.1.1.3 Information interface of vehicle power train components

Finally, the author constructed an information interface DSM of Hybrid vehicle components as shown in Figure 5.6 and applied standard operations to that DSM to create clusters of high information interface components, as shown in Figure 5.7. These DSMs show the importance of the information interactions between different components.

Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Front wheels	A	.	2	2	2	1	2	2	2	2			2		2	
Transmission	B	2	.	2		1	2	2	2	2			2		2	
Planetary power splitter	C	2	2	.		1	2	2	2	2			2		2	
Clutch/brake	D	2			.										2	
Internal Combustion Engine	E	1	1	1		.	1	1	1	1			1		1	
Front motor/Generator	F	2	2	2		1	.	2	2	2			2		2	
Invertor	G	2	2	2		1	2	.	2	2	2	2	2	2	2	2
Accessories	H	2	2	2		1	2	2	.	2	2	2	2	2	2	2
Battery	I	2	2	2		1	2	2	2	.	2	2	2	2	2	2
Rear motor/Generator	J						2	2	2	2	.	2		2	2	2
Rear Differential	K						2	2	2	2	2	.		2	2	2
Front axle	L	2	2	2		1	2	2	2	2			.		2	
Rear axle	M						2	2	2	2	2	2		.	2	2
Controller	N	2	2	2	2	1	2	2	2	2	2	2	2	2	.	2
Rear wheels	O						2	2	2	2	2	2		2	2	.

Figure 5.6: Component-based DSM showing information interface of vehicle power train components

In Figure 5.6, for example, the component A design engineer has an energy interface with components B, C, D, E, F, G, H, I, L, and N, but not with components J, K, M, and O. However, component A design engineer must interact with components J, K, M, and O, because they are in the same chunk. This is inefficient.

Now consider Figure 5.7, which shows a repartitioned version of Figure 5.6. Here, there are three small chunks. Chunk 1 design engineers will not exchange information with chunk 2 design engineers, except for the "systems integration" engineers for components G, H, I, and N1. Overall the three smaller chunks indicate shorter iteration loops, faster development times, and a generally more efficient design process.

Components		O	M	K	J	G	H	I	N1	F	C	B	E	L	A	D	N2
Rear wheels	O	.	2	2	2	2	2	2	2								
Rear axle	M	2	.	2	2	2	2	2	2								
Rear differential	K	2	2	.	2	2	2	2	2								
Rear motor/Generator	J	2	2	2	.	2	2	2	2								
Inverter	G	2	2	2	2	.	2	2	2	2	2	2	1	2	2		
Accessories	H	2	2	2	2	2	.	2	2	2	2	2	1	2	2		
Battery	I	2	2	2	2	2	2	.	2	2	2	2	1	2	2		
Controller	N1	2	2	2	2	2	2	2	.	2	2	2	1	2	2		
Front motor/Generator	F					2	2	2	2	.	2	2	1	2	2		
Planetary power splitter	C					2	2	2	2	2	.	2	1	2	2		
Transmission	B					2	2	2	2	2	2	.	1	2	2		
Internal Combustion Engine	E					1	1	1	1	1	1	1	.	1	1		
Front axle	L					2	2	2	2	2	2	2	1	.	2		
Front wheels	A					2	2	2	2	2	2	2	1	2	.	2	2
Clutch/brake	D														2	.	2
Controller	N2														2	2	.

Figure 5.7: Clustering of information interface in component-based DSM of vehicle power train

5.1.2 Reflex case 2 (Project management)

The author constructed a DSM of Reflex project students, as shown in Figure 5.8 and applied standard operations to that DSM to create student teams, as shown in Figure 5.9. These DSMs show the strength (importance) of the coordination between students.

Figure 5.8 shows the vehicle power train component design engineers identified by name in column 1, and interaction strength is shown with either a 1 or a 2, as was done previously.

In figure 5.8, the component A design engineer has information flow with component B, C, D, E, F, G, H, K, O, P, and Q, but not with component I, J, L, M, and N design engineers. However, component A design engineer *must* interact with component I, J, L, M, and N design engineers, because they are on the same team. This is inefficient.

Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Front wheels	A	.	2	2	2	1	2	2	2			2				2	2	2
Transmission	B	2	.	2	1	1	2	2	2			2				2	2	2
Planetary power splitter	C	2	2	.	1	1	2	2	2			2				2	2	2
Clutch/brake	D	2	1	1	.	2	1					1				1		2
Internal Combustion Engine	E	1	1	1	2	.	1	1	1			1			2	1	1	1
Front motor/Generator	F	2	2	2	1	1	.	2	2			2				2	2	2
Invertor	G	2	2	2		1	2	.	2	2	2	2	2	2			2	2
Battery	H	2	2	2		1	2	2	.	2	2	2	2	2			2	2
Rear motor/Generator	I							2	2	.	2		2	2		2	2	2
Rear Differential	J							2	2	2	.		2	2		2	2	2
Front axle	K	2	2	2	1	1	2	2	2			.				2	2	2
Rear axle	L							2	2	2	2		.	2		2	2	2
Rear wheels	M							2	2	2	2		2	.		2	2	2
Fuel delivery/storage	N					2									.			2
Chassis	O	2	2	2	1	1	2			2	2	2	2	2		.		
Accessories	P	2	2	2	2	1	2	2	2	2	2	2	2	2			.	2
Controller	Q	2	2	2	2	1	2	2	2	2	2	2	2	2	2		2	.

Figure 5.8: Team-based DSM showing information flow between Reflex project design engineers

The author repartitioned the DSM in Figure 5.8 to make smaller teams; this is shown in Figure 5.9, where there are three smaller teams. Team 1 design engineers will not exchange information with team 2 design engineers, except for component G, P, H, and Q1 design engineers. Similarly, team 2 design engineers will not exchange information with team 3 design engineers, except for component E design engineer. Each team can implement its own, relatively short iterative design loop, using team members it shares with other teams as systems integration engineers.

In this way, fewer design engineers will be involved in each team iteration loop, reducing the design iteration cycle time of each team and resulting in a faster development process.

Components		M	L	J	I	O1	G	P	H	Q1	F	C	B	K	A	O2	D	E	N	Q2
Rear wheels	M	.	2	2	2	2	2	2	2	2										
Rear axle	L	2	.	2	2	2	2	2	2	2										
Rear differential	J	2	2	.	2	2	2	2	2	2										
Rear motor/Generator	I	2	2	2	.	2	2	2	2	2										
Chassis	O1	2	2	2	2	.	2	2	2	2										
Inverter	G	2	2	2	2	2	.	2	2	2	2	2	2	2	2	2	1	1		
Accessories	P	2	2	2	2	2	2	.	2	2	2	2	2	2	2	2	1	1		
Battery	H	2	2	2	2	2	2	2	.	2	2	2	2	2	2	2	1	1		
Controller	Q1	2	2	2	2	2	2	2	2	.	2	2	2	2	2	2	1	1		
Front motor/Generator	F						2	2	2	2	2	2	2	2	2	2	1	1		
Planetary power splitter	C						2	2	2	2	2	.	2	2	2	2	1	1		
Transmission	B						2	2	2	2	2	2	.	2	2	2	1	1		
Front axle	K						2	2	2	2	2	2	2	.	2	2	1	1		
Front wheel	A						2	2	2	2	2	2	2	2	.	2	1	1		
Chassis	O2						2	2	2	2	2	2	2	2	2	.	1	1		
Clutch/brake	D						1	1	1	1	1	1	1	1	2	2	.	1		
Internal Combustion Engine	E						1	1	1	1	1	1	1	1	1	1	1	.	2	1
Fuel delivery/storage	N																	2	.	2
Controller	Q2																	1	2	.

Figure 5.9: Clustering of information flow in Team-based DSM of Reflex project design engineers

5.1.3 Summary

The DSMs in figures 5.3, 5.5, 5.7, and 5.9 indicate inconsistency between teams – different perspectives (physical connectivity, energy flow, and information flow) lead to different team arrangements. Yet only one set of teams can be meaningfully implemented. One must resolve this apparent contradiction.

There are a few possible explanations for this.

There could be something wrong with either the system design or strategy used by the Reflex team to treat the design. Given that the Reflex configuration was conceived by student engineers, it is possible that the product strategy was never fully elicited from the student team members; thus it is possible that the inconsistencies noted in the DSMs arose from lack of consistency among the team members who supplied the data. This suggests that the student team might need to reflect more upon the nature of the project.

Similarly, due to their relative lack of experience, the students involved in the Reflex project may lack the experience and expertise in systems design to flesh out their concept for the vehicle; this too might be a cause of the inconsistency.

More specifically, in figure 5.3 team 1 has design engineers of components M, L, J. I, and *O* whereas in figure 5.5 team 1 has design engineers of components M, L, J, I, *G*, and *H*. Is the engineer in charge of component O in team 1 or not? If team members disagree on these matters, management and technical problems could arise. In this scenario, one might even suggest that combining these teams could reduce variations among them.

It may be the case, however, that there are no significant problems with either the strategy or systems design (or at least none that can be readily identified). In this case, we might consider merging corresponding teams from the different DSMs. In other words, all the team 1's from each of the materials, energy, and information perspectives would be merged into a single team 1. Then in these new teams the design engineers of components G, P, H, E, and Q have shared responsibilities assume the role of system integration engineers. So design engineers for these positions have experience in system integration.

Clearly a number of alternatives to clarify the Reflex project could have been possible. However, the author did not have the opportunity to pursue this matter.

5.2 The DSM and Axiomatic Product Development Ltd

5.2.1 Overview

Axiomatic Product Development Ltd (APD), a product engineering firm in the Greater Toronto Area, has undertaken the design of a Tailgate Latch Assembly (TLA) for trucks.

5.2.2 Analysis of the current design

The author began with the existing design of the TLA. The author interviewed an APD employee who was acquainted with the TLA to understand the geometry and function of its parts. The author then constructed a DSM of the existing design and applied standard operations to that DSM to create *clusters* of highly interacting parts.

Figure 5.11 shows the Tailgate latch assembly parts identified by name in column 1. In this application, the strength of an interaction is defined with respect to part function. A *strong* interaction is one that is essential for the TLA as a whole to function properly; other interactions are *weak*.

Components		A	B	C	D	E	F	G	H	I	J	K	L	Sum
Latch housing	A	.	2	2	2	2	2	2	1	2	2			17
Ratchet and Pawl Rivet (Left side)	B	2	.	2			2	1	1					8
Pawl Spring	C	2	2	.			2	1	1					8
Ratchet Spring	D	2			.	2	1	2						7
Ratchet and Pawl Rivet (Right side)	E	2			2	.	1	2						7
Pawl	F	2	2	2	1	1	.	2	2		1	1		14
Ratchet	G	2	1	1	2	2	2	.	1	1				12
Lever	H	1	1	1			2	1	.	2	1	2	1	12
Lever Rivet	I	2					1	1	2	.		1	1	8
Bumper	J	2					1		1		.			4
Clip	K						1		2	1		.	2	6
Rod	L						1		1	1		2	.	5

Figure 5.11: Component-based DSM showing materials interactions for Tailgate latch assembly

In Figure 5.11, the column labeled *Sum* indicates a Relative Significance Summation Clustering (RSSC). It includes the following steps.

The current design of the assembly has 12 parts. The author studied the current design to improve it in substantive ways through the use of the DSM. The author proposes that an improvement would see a reduction in part count from 12 to 10 (and possibly more). This improvement represents a potential increase in product robustness and a decrease in overall product cost. It also has positive implications for project management as well as cost and time control of product development. While further work is needed to flesh out the proposed changes, the author believes his solution is a feasible one and could noticeably and positively impact the product.

The "as-is" TLA configuration is shown in Figure 5.10.

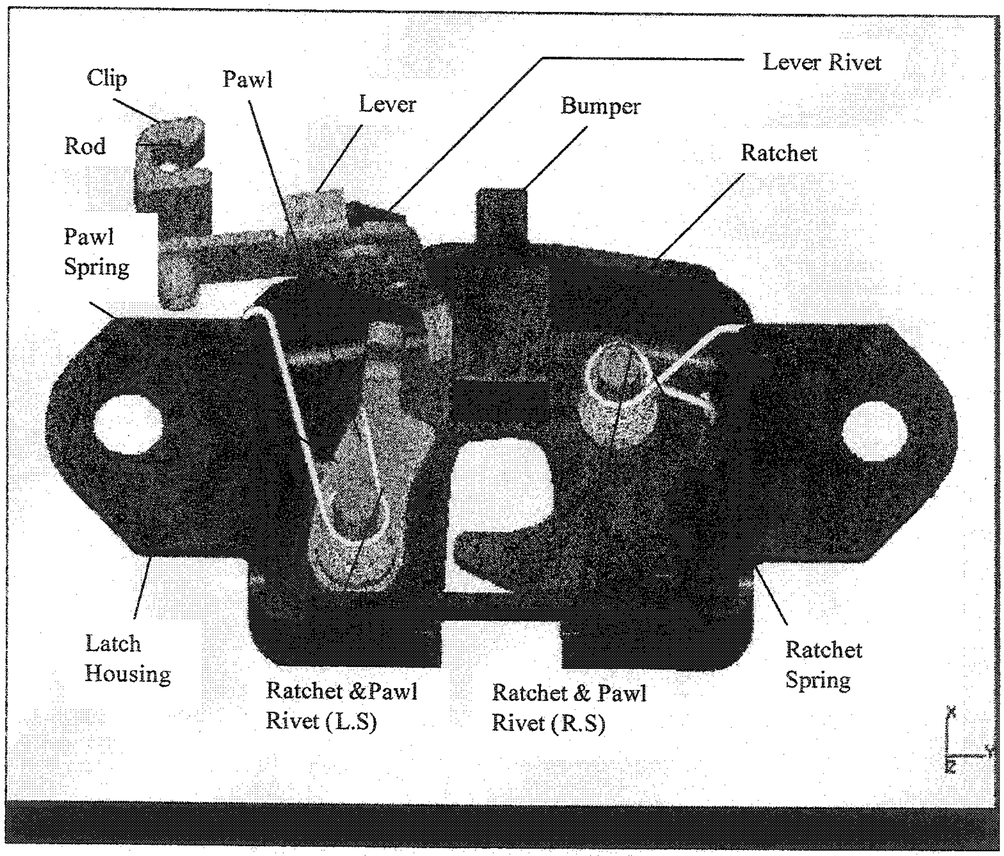


Figure 5.10: Tailgate Latch Assembly

a. Assign values to DSM cells that reflect qualitative or quantitative importance of an interaction. For the TLA, we did a qualitative measure (1 or 2).

b. Create a new column, each cell of which contains the sum of the cell values in the DSM proper. All the information in a given row indicates the relative amount of interaction of one part (the part for that row) with respect to the entire product (all the columns that intersect that row). So the sum of all that information is a single relative measure of the degree of interaction of one part with respect to the whole product.

c. Look for gaps in the distribution of the sums, i.e. look for clusters of sums. The clusters represent groups of parts that have similar degrees of interaction. The cluster with the highest values is the group of parts that most strongly interact in the product.

d. These are the parts that are the most logical candidates to be combined into one part.

The RSSC shows that the Latch Housing (A), Pawl (F), Ratchet (G), and Lever (H) have a total interaction strength higher than other components. These components, then, may be seen as more critical The sum of dependency strength of components A, F, G, and H suggests that the design engineers of these components will (or, at least, *should*) spend more time in the development process than other component design engineers. It also shows that the coordination cost in terms of number of hours will likely be higher, compared to other component design engineers. Finally, it suggests that the design engineers of these components will exchange information or communicate with all other components design engineers.

Figure 5.12 shows the manipulated DSM. Components B, C, D, and E are in same chunk (chunk 1), but components B and C have no interaction with components D and E. Components A, F, G, and H have interactions with components B, C, D, and E. Similarly, components A, F, G, and H have interactions with components I, J, K, and L, but components B, C, D, and E have no interactions with components I, J, K, and L. Chunks are still "sparse," and we would prefer them to be more dense.

Components		C	B	D	E	G	A	F	H	I	J	K	L
Pawl Spring	C	.	2			1	2	2	1				
Ratchet and Pawl Rivet (Left side)	B	2	.			1	2	2	1				
Ratchet Spring	D			.	2	2	2	1					
Ratchet and Pawl Rivet (Right side)	E			2	.	2	2	1					
Ratchet	G	1	1	2	2	.	2	2	1	1			
Latch Housing	A	2	2	2	2	2	.		1	2	2		
Pawl	F	2	2	1	1	2	2	.	2		1	1	
Lever	H	1	1			1	1	2	.	2	1	2	1
Lever Rivet	I					1	2	1	2	.		1	1
Bumper	J						2	1	1		.		
Clip	K							1	2	1		.	2
Rod	L							1	1	1		2	.

Figure 5.12: Clustering of materials interactions in Component-based DSM of Tailgate latch assembly

Figure 5.13 shows a further manipulation of the DSM. There are now four small chunks, and these chunks are much denser compared to the chunks of figure 5.12. It shows that four of the parts have duplicate entries. This is because components B, C, D, and E have interactions with components A, F, G, and, H but components B and C have no interactions with components D and E. Similarly, components I, J, K, and L have interactions with components A, F, G, and H but I, J, K, and L have no interactions with B, C, D, and E. This duplication does *not* hide or bias the relationships among parts. It is done to ensure that clusters are as densely populated with non-blank entries as possible, making the clusters as small as possible. Small clusters (i.e., those having few parts) have been shown to be characteristic of superior products.

Components		B	C	H1	F1	G1	A1	D	E	G2	A2	J	F2	H2	I	K	L
Ratchet and Pawl Rivet (Left side)	B	.	2	1	2	1	2										
Pawl Spring	C	2	.	1	2	1	2										
Lever	H1	1	1	.	2	1	1										
Pawl	F1	2	2	2	.	2	2	1	1								
Ratchet	G1	1	1	1	2	.	2	2	2								
Latch Housing	A1	2	2	1	2	2	.	2	2								
Ratchet Spring	D				1	2	2	.	2								
Ratchet and Pawl Rivet (Right side)	E				1	2	2	2	.								
Ratchet	G2									.	2		2	1	1		
Latch Housing	A2									2	.	2	2	1	2		
Bumper	J										2	.	1	2			
Pawl	F2									2	2	1	.	2	1	1	1
Lever	H2									1	1	2	2	.	2	2	1
Lever Rivet	I									1	2		1	2	.	1	1
Clip	K												1	2	1	.	2
Rod	L												1	1	1	2	.

Figure 5.13: Clustering of materials interactions in Component-based DSM of Tailgate latch assembly

In Figure 5.13, there are four small chunks. Each chunk suggests a small, relatively quick design iteration cycle, and the overlapping components are those essential for systems integration of the whole assembly.

The design iteration process that is implied in Figure 5.13 is such that the team for each chunk can have its own relatively small iteration loop. Each cycle results in a change to the design. The changes must be passed on to other teams. Since we have assumed one design engineer per component, it is an easy matter to determine which team members must be advised and consulted with regarding design changes based on the components the designs of which have changed. Synchronizing these changes ensures that the individual iteration loops of each team feed information forward to other teams in a timely and efficient manner. The details of such synchronization involve workflow analysis and design as well as matters of organizational and management sciences, and are beyond the scope of this thesis. The key matter to be recognized is that it is the use of the DSM that was responsible for identifying the features of this design task that subsequently led to these potential design process improvements.

Figure 5.13 also shows four partially overlapping clusters. Each cluster represents a group of parts whose design must be closely coordinated because all the parts in each cluster interact strongly, so changes to one part in a cluster will significantly affect the other parts. Conversely, changes to one part in one cluster will *not* affect parts in any other clusters. This impacts significantly on project management in that the clusters can be used to guide how information is distributed to design team members and how workflow can be organized. This can help control and reduce lead-time. Also, Figure 5.13 suggests that, for a product of this level of complexity, one might have four designers working on the product, one for each cluster, with a minimum of interactivity among them. The designers would only have to interact with one another when working on parts that appear in multiple clusters. The parallelism that can be achieved based on the relative independence of the clusters can further shorten lead-time. However, even if a single designer is assigned to this project, that designer can better organize his thoughts and activities by knowing how the different parts interact. Furthermore, each cluster may be treated as a subassembly, where the individual subassemblies are connected through parts that are shared by multiple clusters. That is, parts that are in multiple clusters constitute "system interface components." Thus, to improve assemblability of the product, particular attention needs to be paid *only* to those parts (in this case, parts A, F, G, H, and I, only half of the total number of parts).

Figure 5.13 shows that chunks 1 and 2 are disconnected from chunks 3 and 4. The arrangement in Figure 5.13 shows that if there are three design engineers for the Tailgate latch assembly, design engineer 1 deals with components B, C, D, and E; design engineer 2 deals with components A, F, G, and, H; and design engineer 3 deals with components I, J, K, and L . However, design engineer 2 will exchange information with both design engineers 1 and 3.

Figure 5.14 shows that Ratchet and Pawl Rivet (Left side), Pawl Spring, Latch Housing, and Pawl have strong interactions with each other. These components have strong physical interactions with each other and work like a single component. The author considered blending them.

Components		B	C	F	A
Ratchet and Pawl Rivet (Left side)	B	.	2	2	2
Pawl Spring	C	2	.	2	2
Pawl	F	2	2	.	2
Latch Housing	A	2	2	2	.

Figure 5.14 Component-based DSM showing physical interaction between components

Figures 5.15 and 5.16 show one component Leaf spring instead of three components Ratchet and Pawl Rivet (Left side), Pawl Spring, and Pawl.

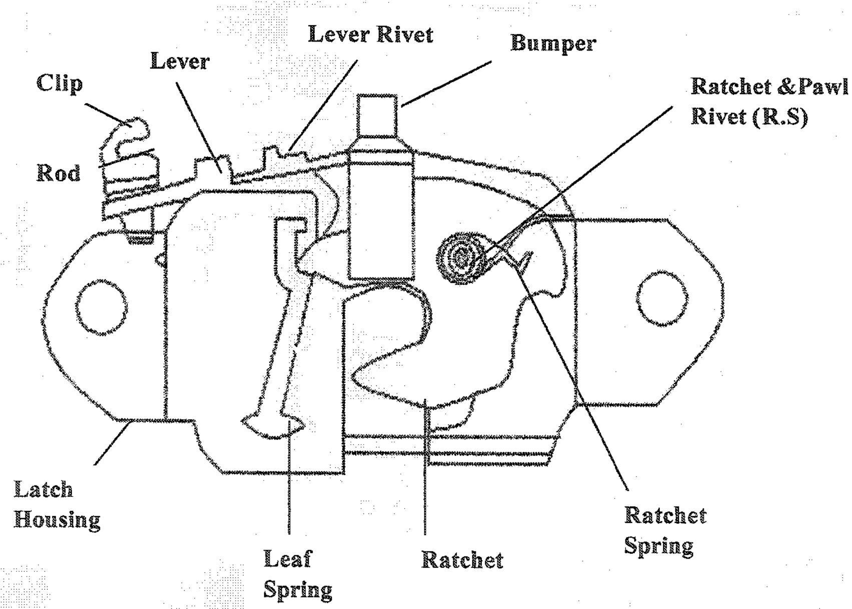


Figure 5.15: Tailgate latch assembly proposed design sketch

Components		A	B	D	E	G	H	I	J	K	L	Sum
Latch Housing	A	.	2	2	2	2	1	2	2			13
Leaf Spring	B	2	.	1	1	2	2	1	1	1	1	12
Ratchet Spring	D	2	1	.	2	2						7
Ratchet and Pawl Rivet (Right side)	E	2	1	2	.	2						7
Ratchet	G	2	2	2	2	.	1	1				10
Lever	H	1	2			1	.	2	1	2	1	10
Liver Rivet	I	2	1			1	2	.		1	1	8
Bumper	J	2	1				1		.			4
Clip	K		1				2	1		.	2	6
Rod	L		1				1	1		2	.	5

Figure 5.16: Component-based DSM showing materials interactions for Tailgate latch assembly

Figure 5.17 shows that chunk 2 is still "sparse." We would prefer it to be denser.

Components		D	E	G	B	A	H	J	I	K	L
Ratchet Spring	D	.	2	2	1	2					
Ratchet and Pawl Rivet (Right side)	E	2	.	2	1	2					
Ratchet	G	2	2	.	2	2	1		1		
Leaf Spring	B	1	1	2	.	2	2	1	1	1	1
Latch Housing	A	2	2	2	2	.	1	2	2		
Lever	H			1	2	1	.	1	2	2	1
Bumper	J				1	2	1	.			
Lever Rivet	I			1	1	1	2		.	1	1
Clip	K				1		2		1	.	2
Rod	L				1		1		1	2	.

Figure 5.17: Clustering of materials interactions in Component-based DSM of Tailgate latch assembly

Figure 5.18 shows the duplicate of components B and H, because components B and H have interactions with components D, E, G, A, J, I, K, L and A, but components D and E have no interaction with components J, I, K, and L. Similarly, components G and A have interactions with components D, E, J, and I, but components G and A have no interactions with components K and L This duplication does *not* hide or bias the relationships among parts. Rather, it ensures that clusters are as densely populated with non-blank entries as possible, making the clusters as small as possible.

The design iteration process of Figure 5.18 shows that chunk 2 will perform the iteration cycle first and then freeze the iteration process, giving the results of the iteration to chunks 1 and 3 through design engineers G, A, B1 and I. Then chunks 1 and 3 will perform their iteration cycles, freeze their iteration cycles, and give the iteration results back to chunk 2 through design engineers G, A, B1, and I and repeat the procedure.

Components		D	E	G	A	B1	H1	J	I	K	L	B2	H2
Ratchet Spring	D	.	2	2	2	1							
Ratchet and Pawl Rivet (Right side)	E	2	.	2	2	1							
Ratchet	G	2	2	.	2	2	1		1				
Latch Housing	A	2	2	2	.	2	1	2	2				
Leaf spring	B1	1	1	2	2	.	2	1	1				
Lever	H1			1	1	2	.	2	2				
Bumper	J				2	1	1	.					
Lever Rivet	I			1	1	1	2		.	1	1	1	2
Rod	K								1	.	2	1	2
Clip	L								1	2	.	1	1
Leaf spring	B2								1	1	1	.	2
Lever	H2								2	2	1	2	.

Figure 5.18: Clustering of materials interactions in Component-based DSM of Tailgate latch assembly

5.2.3 Seeking improvements

One possible solution is to machine a flexible tongue onto the latch housing. The tongue would act as spring because it would be flexible, but it would also act as a lock. There is a problem with this solution, however. The tongue increases the complexity of the latch housing, especially with respect to manufacturability and maintainability. The complex geometry requires more detailed analysis and costlier tooling and machining. It also limits material selection. Maintainability is decreased because a failure of the integral tongue would minimally require replacing the entire latch housing.

The author then modified his concept as a *separate* tongue that would be press-fitted into the latch housing. While it adds one more part than an integrated tongue, the approach still has a number of benefits. First, the part count of the TLA is still reduced by 2. Second, as the tongue is a separate part from the latch housing, manufacturing and machining costs will be lower than for the integrated tongue. Third, the tongue's material can be chosen to optimize its performance and minimize its size. Indeed, based only in a qualitative sense on the operating loads on the parts, it may be possible to use a plastic for the tongue, providing a further potential reduction in manufacturing costs.

The proposed solution is sketched in Figure 5.15. The precise size and shape of the tongue cannot be defined without further information about the operating loads and manufacturing (and other) constraints, which was not available to the author at the time of writing.

The author then reconstructed the DSM for his solution; this new DSM is shown in Figure 5.18. The new design requires only three clusters, instead of four. This leads us to believe that all the potential improvements indicated in Section 2 will be amplified by moving to the new design. The degree of improvement, however, cannot be forecast at this time.

Finally, since this new design represents an innovation, it may take time for APD to become comfortable with it. However, the author suggests that an early success with a new TLA design will lead to further opportunities to apply this kind of solution to other products. The corporate expertise that will be gained will allow future products to be developed with increasing efficiently.

5.2.4 Further improvements

Assuming the strategy of the proposed design—replacing many parts with single multi-disciplinary parts—is feasible, given material, manufacturing, and other constraints, further improvements may be possible.

Consider the parts in the top-left cluster of Figure 5.18. Except for the (new) tongue, the parts all interact strongly with each other. These parts are functionally similar to the parts that were replaced by the tongue.

If a similar strategy can be adopted for the ratchet and its related parts, it may be possible to replace the ratchet, ratchet spring and rivet, *and the new tongue itself*, with a single part that is flexible in bending and stiff in compression. This could reduce the top-left cluster to a *single* part and lower the total part count of the TLA from 12 to only 6. Although this approach is radical, it could also lead to a substantial innovation in this class of product.

5.2.5 Recommendations

The author has used the design structure matrix to analysis a Tailgate latch assembly. The author's recommendations are:

1. Implementing a design team and workflow based on the clusters in either Figure 5.13 or Figure 5.18 will improve the development process for this class of product.
2. Design for assembly issues should be focused primarily on those parts indicated by the DSM as system interfaces.
3. It should be possible to replace the pawl and related parts with a single tongue, lowering the part count from 12 to 10.
4. More substantive improvements may be possible, potentially lowering the part count by 50%.

Chapter 6 Summary and Conclusions

The goal of this thesis is to apply the design structure matrix, which is identified as a best design practice, to the field of automotive engineering. The author's original thesis topic involved the much broader field of best design practices in general; however, due to problems within the Auto21 project wherein the author's thesis originated, the topic had to be adjusted.

In general, little work has been done on best practices for design engineering, but there is significant potential for improvement if such research were to be conducted in the future. While associated with Auto21, the author was to find and use a tool suitable to the design of a novel gas/electric hybrid power train, with respect to project management and systems design. The *design structure matrix* was identified as the best tool for this purpose. Three cases were considered, two regarding the Auto21 hybrid vehicle project and a third regarding the design of a tailgate latch assembly. In all three cases, a number of substantive recommendations were developed to improve the design process, team deployment, or systems design of the artifact being designed.

The author's contributions are:

- A novel feature Relative Significance Summation Clustering (RSSC) of DSMs was discovered. To the author's best knowledge, this feature has not been reported in the DSM literature, and could constitute a further advance in the use of DSMs. In cases were DSM cells contain weighted values of interactions, one can sum the weights to establish a total degree of importance of each component with respect to the whole. One can further use those sums to guide the selection of components that might be grouped in specific ways, per the conventional rules and methods of DSM analysis.
- The Relative Significance Summation Clustering (RSSC) of DSMs was used to lower the number of parts in assemblies. This has not been reported in the literature to the author's best knowledge.
- The author has shown that taking different perspectives (material, or energy, or information interactions) can lead to different team structures, i.e. the author has discovered a problem with the DSM – depending on the nature of the interactions, one can get conflicting results. The author aslo additionally suggested ways that

these conflicts can be resolved. The particulars of any given solution will depend on the problem.

- The author has applied the DSM method to the development of teams for the Reflex project, and makes specific recommendations as to how the teams should be established. While team-based DSMs have been used before, it has never been used to develop teams of students who are of different levels of expertise and located in different geographic regions. The author results *suggest* that the DSM can be used successfully to create student teams just as it can be used in industry.
- The author made recommendations regarding how the design of the Reflex power train should proceed – i.e. a design process (where one chunk/team starts, then freezes its design and passes it off to the next group, and so on.

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Appendix A: Case Studies of Best Practices

The following best practices have implemented in different organizations.

1. Flexible weekend shift work

This Best Practice is adapted from [16].

Dayton parts Inc. (DPI) needed additional plant capacity on critical manufacturing processes. Already operating at almost full capacity, DPI would have to add more workers to weekend shifts. Rather than hiring part-time employees to staff the plant on weekends or working full-time employee overtime, the company used a creative employee schedule technique similar to one used by hospitals to staff nurses on weekends **(Principle: look for scheduling solutions in other industries or sectors).**

Under this plan, full-time employees work a 12-hour shift on Saturday, a 12-hour shift on Sunday and two, eight- hour shifts on flexible weekends. As an incentive to work this non-traditional work schedule, employees are paid for 45 hours per week while actually working 40.

DPI currently has five employees on this schedule, and both the employees and the company have realized many benefits, some of which were not envisioned when the program was established.

Employees now have three days off from work each week, and the non-weekends days are flexible.

This flexibility allows management to give employees off days to suit individual needs. In other weeks, these employees work certain days to cover for other workers on vacation.

The weekend's workers are cross-trained to operate many different machines in the plant and have become competent at maintaining and repairing the equipment they use since the maintenance staff does not normally work weekends.

This allows the weekend workers to produce whatever parts are most needed to meet production schedules.

Comments

This principle allows management to give employees off days to suit individual needs.

Employees are paid for 45-hours per week while actually working 40-hours.
Employees have flexible non-weekend days with three days off from each week.
This principle makes employees more competent for maintaining and repairing different machines and equipment's.

2. Worker Safety improvement program

This Best Practice is adapted from [16].

Prior to the 1990s, Dayton parts, Inc. (DPI) had no worker safety program, and injuries were viewed as a natural part of manufacturing. In the early 1990s, new DPI management and staggering worker's compensation costs promoted the company to aggressively pursue and manage worker safety. Many initiatives were implemented to reduce injuries and resultant costs.

The primary goal of the safety program is to increase safety awareness at DPI. The following initiatives, designed to help DPI meet its goal, are supported by a strong company commitment to safety, **(Principle: strong commitment at all level of company)** and an executive safety committee that meets quarterly to address current safety problems, and works with maintenance personnel to have those problems repaired.

A 'stretching' program is required for all-manufacturing distribution and service employees to stretch prior to starting production work each day to help avoid work-related injuries **(Principle: Treat all manual labour as intensive exercise).**

A 'working safe' incentive program rewards safe workers. After one year without a lost-time accident, workers become eligible to win a 'safety Day' off from work in a monthly lottery, or a $ 100 bonus at the end of the year **(Principle: Recognise professional behaviour)**

A housekeeping committee monitors the cleanliness of the manufacturing plant. This program has evolved into a competition for the cleanest department in the plant.

A formal safety-training program includes monthly meetings where short videos are shown and safety issues are discussed. Longer training classes have been established for topics such as forklift operation, personal protective equipment, and back injury avoidance.

When injuries occur, DPI now works closely with the injured employee to be sure he receives the necessary medical attention and returns to work when able. A case manager ensures that the injured employee sees a doctor on the approved list and accompanies the employee to the doctor's office. DPI makes weekly phone contact with the employee when he is not able to work. In addition, light duty jobs are created to provide productive work while employees are under injury restrictions. **(Principle: Do not isolate injured workers from rest of company).**

In 1988, DPI had 1000 days of lost due to injuries. After the safety program took effect, the number of days dropped substantially to 91 days in 1993 and 69 days in 1994.

Comments

The safety improvement program help to increase safety awareness, reduce injuries during work, reduce the number of lost days due to injuries, minimize the production loss due to injuries, and increase overall efficiency of an organization.

3. Customer Satisfaction interview process

This Best Practice is adapted from [17].

1994, Cincinnati Milacron began a customer satisfaction survey. The survey, developed and performed by an outside consultant, was conducted by telephone and focused on products, which the customer had in service for six months to one year. Questions dealt with Cincinnati Milacron's products as well as its competitors.

In 1996, Cincinnati Milacron initiated monthly surveys, conducted by employees who are members of the Customer satisfaction team. This is a special group that has been established to obtain feedback from customers about their satisfaction with Cincinnati Milacron's products and service, as well as their perceptions about the company and its distributors in general. About 40 customers are surveyed each month in reference to specific machine tools that were installed in their plant. The interviewer asks about 40 questions on satisfaction and perceptions using a ten-point scale, ranging from and quotextremely satisfied" to & quotnot satisfied at all" for each answer. Results are carefully reviewed by customer service personnel, engineering staff, and management. Information from the survey is used as an input to measure the effectiveness of the managers of each business unit **(Principle: use customer surveys to rank management as well as workers).**

Cincinnati Milacron's customer satisfaction telephone interviews have provided excellent feedback and very useful information. Customers that indicate strong disapproval receive prompt attention, which can prevent the loss of a customer. Distributor problems and weaknesses in sales coverage can be an excellent tool for continuous improvement and measuring customer satisfaction.

Comments

The customer satisfaction survey provides excellent feedback and information to the company about their products and services.

The survey help to indicates the approval and disapproval of the products and also distributor problems and weaknesses.

The customer survey information is used as an input to measure the effectiveness of the managers of an organization.

The customer satisfaction survey is an excellent tool for the continuous improvement of an organization.

4. Dynamic Quality System

This Best Practice is adapted from [18].

Cincinnati Milacron's Machine tool Group (MTG) has developed and implemented a dynamic quality system based on the documentation of all processes, conformance measurements, and continuous improvements. **(Principle: Keep documentation current)** Until about three years ago, the MTG'S quality system was poorly documented, poorly controlled, and haphazard. Besides lacking trained auditors, the system had no formal method for handling non-conforming material; corrective and preventive action; or internal control.

Cincinnati Milacron's new approach to quality began in 1994 with the objective of becoming ISO-9001 certified. The Dynamic Quality System was designed to be a fully documented system with processes for internal auditing, corrective action, non-conforming material, and machine audits. The system is based on the corporate vision and supports the MTG quality policy, which focuses on customer satisfaction, conformance to requirements, and continuous improvement.

The focal point of the system is the quality documentation system. Over 300 documents containing policies, manuals, operating procedures, and work instructions are available on-line and in hardcopy at 30 quality documentation centers located throughout the facility. The on-line system uses a commercially available documentation software program. The combination of the on-line and hardcopy documents ensures that essential information is accessible to everyone who needs it and can be easily updated. Operating procedures and work instructions are available for all equipment and processes in the plant. All work is considered a process and must be documented.

The quality documentation system is reinforced by an effective, internal quality audit process. Nearly 50 internal auditors have been trained. They operate in teams of two, and conduct internal quality audits of key functional areas and processes. Annual audits cover all ISO certification status is maintained. All audit non- conformances are analyzed to determine root causes, and appropriate corrective action is initiated.

The MTG has closed-loop processes for corrective action requests, non- conforming material, machine audits, and customer satisfaction.

Corrective action requests and non-conforming material reports must be closed out within 30 days. Machine audits and 24 to 40 hours of reliability and verification testing are done on each machine before it is shipped. These processes form feedback loops to all levels of the company from the supplier chain to equipment in the field.

Cincinnati Milacron's Dynamic Quality System provides clearly defined documented policies and procedures, and a baseline for continuous improvement. Well-defined methods for handing corrective action, non- conforming material, and performing audits are clearly specified. The system provides internal control of conformance to requirements; allows for flexibility and variation; and provided the basis for successful achievement of ISO-9001 certification in April 1996.

Comments

The Dynamic Quality System is fully documented system with clearly defined polices, procedures, work instructions, corrective actions (CAR'S), non-conforming materials, internal audits, and machine audits.

The system clearly defined company Quality police about customer satisfaction, conformance to requirements, and continuous improvement.

The Dynamic Quality System provides the basis for successful achievement of ISO-9000 certification.

5. Implementing a compressed air system leak management program at an Automotive plant

This management case study is adapted from [19].

The Monroe plant, located in Monroe, Michigan. The Plant energy team is made up of volunteers, most of whom are plant employee of Ford motor land Development Corporation and visteon's utility, Detroit Edison. An energy coordinator from the plant whose objective is to reduce energy waste leads the team. Once the team at the Monroe plant was formed, their first target was the leaks in the plant's compressed air system. They gathered the baseline data, both during production and during a holiday shutdown, so they could estimate the cost of compressed air and calculate the loss due to air leaks. **(Principle: Quantify a problem before trying to fix it).**

"The upper management bought red "energy team". Jackets for every team member, which helped them stand out in the plant and gave them a special identity. **(Principle: special identity for special jobs a kind of reorganization)** While they developed this identity, they never lost sight of the fact that their goal was to make every employee a member of the energy team. They include their colleagues in a cooperative framework that made it apparent to everyone in the plant that they were there to help instead of to criticize".

To make the program, the team developed a procedure for all employees to report leaks. They used items like buttons, hats, tee shirts, key chains, and refrigerator magnets to promote the program and reward employees for helping and becoming part of the team.

They posted "leak boards" in several locations in he plant that had been identified and repaired. The black dots on the board became symbols of progress.

The energy team also developed posters to illustrate the cost of air leaks, as well as other causes of energy waste. **(Principle: maintain positive visibility for change initiatives).** They took charts from the compressed air and gas institute, developed fact sheets on the cost of air leaks, and passed them out to the employees. They also used their company's communication network to develop messages that were shown on the monitors throughout the plant. In addition, the team developed stickers and placards for proper shutdown of equipment and gave presentations on energy saving measures.

"The most important part of this story is that team used top-down support combined with bottom-up implementation". They made everyone aware, but concentrated their efforts on the people who had the knowledge of the equipment and could make the necessary changes in the plant's institutional culture.

Results

When the program started in the 1989, the plant used 17.4 million cubic feet (mcf) per day. By 1992, air consumption had been reduced to 9 million cubic foot per day. After completing the project, the plant was able to take three reciprocal compressors totaling 1550-hp offline, base load a 2500-hp centrifugal compressor and used an 800-hp centrifugal compressor for peak needs. This represents savings of almost $1700 per day during the week and $ 1200 per day on weekends and 11.5% of electricity costs. Non-production compressed air consumption was reduced from 5400 cfm to less than 600 scfm (standard cubic feet per minute).

Comments

The air leak management program builds successful awareness about compressed air energy.

The leak management helps to identifying and repairing air leaks, which can be significant source of wasted energy.

Air leaks continue to occur, so leak management program need to be continuous efforts and are very important in maintaining the efficiency, reliability, stability, and cost effectiveness of any compressed air system.

The compressed air baseline data is necessary for the improvement of the system.

The baseline data for production facilities would be air usage per unit of production and for non-production facility air usage per time (hour, day, month, year) or per area (square feet or meter).

6. Quick Mold Change

This Best Practice is adapted from [20].

Nascote, as a high production supplier of automobile parts to several manufactures, accommodated almost 900 tooling changes per year at 1.8 hours per change. To decrease the tooling change time and increase productivity, a team was formed with a superintendent, supervisor, technician and one tool changer from each shift to determine how to reduce the required time for changing molds weighing in excess of 30 tons. **(Principle: team composition should include a variety of experts from broad range of fields, and representatives of all stakeholders).**

The team applied an' AS Is' analysis technique. First, the team mapped a common tool change through each team member explaining his/her specific role during the tool change. The next step required the accurate timing of an actual tool change, noting all problems encountered during the change process. The process reflected the 1.8 hours needed to complete a mold change from the last part of the previous tool to the first acceptable part of the subsequent tool. This figure became the corporate baseline for process improvement initiatives **(Principle: establish baselines before implementing any changes).**

The 'As Is' analysis also reflected:

Twelve steps within the current process

A 20-minute delay while the mold was brought to operating temperature.

Employees involved in the change process had limited skills.

Variety of hose lengths were needed for the water connection.

Ergonomic implications from attaching 30-pound swivels above waist level.

Slippage from fluids lost during mold changes created safety concerns.

Irregular regulator and electrical connections.

Markings for connections needed to be made.

16 large bolts were needed to secure the mold to the press.

60-pound impact gun was needed to secure these bolts.

Tool changer had to lay on his/her back under the mold.

Acquiring the initial location of the mold on the stationary platen was difficult.

Physical arrangement of the tool changer's tool box was important.

Inability to locate the tool changer due to rotational assignments was a problem.

Scheduling did not provide ample notice for change preparation.

Armed with management's endorsement and a 30-day time line for implementation, the team developed a four-day, continuous process improvement plan. Each task was assigned to one or two members for action with a milestone for completion. The team met on a regular basis to monitor progress and provide resolution of problems encountered during the improvement process. To better develop a target of improvement, the team benchmarked two companies with a similar product line and mix.

As a result of its commitment, Nascote has become the model for companies of similar size, product, and part mix. The findings of the 'As Is' state have provided the company with the perfect state, or current six-step process.

In addition, using an existing pre-heater eliminates the 20-minute heating delay, and mold changers are trained to open and close the press instead of a technician. There are common locations and hard connections for water connections to allow standardized hose lengths. **(Principle: standardize parts)** Swivels are delivered prior to the molds to reduce handling, and non-slip surfaces reduce possible injuries. Regulator and electrical connections are positioned at the same location on each mold, and all water connections are marked 'in' and 'out' to eliminate connection errors. Hydraulic clamps have been designed to eliminate the 16 mounting bolts, and a more suitable impact gun has been procured. Common connection locations have eliminated the need for tool changers to lie on their backs under the molds during the change process, and location positions painted on the stationary platen have simplified the initial location of the mold. The company purchased a new cart for the tool changer's tools and tools to be ergonomically located. Tool changers have been reassigned to the re-grind room to make them accessible without disrupting the product flow. And finally, scheduling has been prepared to provide a two-hour notice to allow sufficient change preparation.

Results

The changes implemented resulted in a process with a completion time of less than 0.52 hours, reflecting a time saving of 29% per mold change. This savings, multiplied by the number of tool changes performed, netted a dollar savings of $215,040 per year. The increased capacity now available effected a cost avoidance of $3 million because an additional molding press purchase was no longer necessary. Faster tooling changes also reduced the company's product inventory. With an improvement of this magnitude, Nascote has now changed its tool specification book to ensure all future molds procured are designed for their perfect state tool change process.

Comments

By implementing the Quick Mold Change practice, Nascote has reduced the 12-steps tool change process into 6-steps process.

The Quick Mold change practice reduces the tooling change time, reduces the company product inventory, and increase productivity.