Network Analysis of Technical and Organizational Configurations: Using an Alignment Approach to Enhance Product Development Performance

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To my mom and dad, Lupita & Ezequiel
and my siblings, Laura E.& Ezequiel

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ABSTRACT

In an attempt to improve their Product Development Processes (PDPs), many companies make considerable investments to have available cutting-edge technology such as virtual tools. While some companies have increased their productivity and time to market with them, some others have not. There seem to be fundamental factors above and beyond the use of these tools that can obstruct the PDP and one of them appears to be the misalignment between the product architecture and the organizational interactions of the actors working on it. While there has been significant work addressing the technical and social concerns of a PDP independently, the nature of the misalignment requires an integrated analysis of the product architecture and the organization. The present work studies them in an integrated approach by making use of network analyses.

The research for this thesis was conducted in a Global Product Development (GPD) project of an automotive manufacturer. By first using as a reference the Multidisciplinary System Design Optimization (MSDO) to decompose the architecture of a product and then, using a specific type of Design Structure Matrix (DSM) [43] called

N^2 Diagram to identify the interfaces of the architecture, a network called *theoretical sociogram* was created. In addition, the relative sensitivity of some objectives describing the functioning of the product's systems was calculated to classify the strength of the ties in two levels: *strong* for those above an absolute relative sensitivity of *0.5*, and *weak* for those with an absolute relative sensitivity lower or equal than *0.5*. Furthermore, through surveys and interviews, the organizational interactions for two different phases of the project were mapped to construct a new set of networks called *actual sociograms*. By comparing the sociograms and utilizing metrics that deal with the centrality of the actors in the network, the misalignments were identified.

The misalignments provided guidance to identify the enablers and obstacles influencing the PDP. It was observed that, in some cases, when the sensitivity among variables was *weak*, engineering teams tend to use intermediaries to share information. In some other circumstances the direct interaction doesn't occur, due to reasons including cultural aspects, complexity of the information, the way the information is structured and organizational fuzziness, among others. Based on these findings, some recommendations based on literature review, lessons learned from other industries and conversations with Product Development (PD) actors, are provided.

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And here I am, writing the last words of an exciting and enriching endeavor whose end seemed so far away. Now, I face a new challenge: expressing in a few paragraphs, as if this could be possible, my gratitude to all those who played an important role in reaching this point. Numerous valuable individuals took the time in some way or other to facilitate what sometimes felt like an uphill battle. To all of them, I want to say thank you for all your attention. In particular, I would like to express my gratitude to a few more individuals:

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Finally, my siblings, ***Laura E.*** and ***Ezequiel,*** who have constantly introduced me to new thoughts and new perspectives on the world. I learn so much from them every day, and this has been critical in my life, especially in these last two years. They have been extraordinary role models and I want to thank them for unconditionally extending their hand to me in any circumstance.

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ACRONYM / ABREVIATION	DEFINITION
Aero	Aerodynamics
AIAA	The American Institute of Aeronautics and Astronautics
Arch.	Architecture
AUS	Australia
Betweenn.	Betweenness
BWB	Blended-Wing-Body aircraft
c.g.	Center of Gravity
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAS	Computer-Aided Styling
CC	Change Control
CE	Concurrent Engineering
CE (in sociograms)	Chief Engineer
CFD	Computational Fluid Dynamics
CHN	China
CRD	Component Requirements Document
D&R	Design and Release
d.l.	Dimensionless
DSM	Design Structure Matrix
Dur	Durability
E	Europe
EM	Engineering Manager
Eng.	Engineering
ETF	Economic Testing Frequency
FEA	Finite Element Analysis
FEM	Finite Element Method
FMVSS	Federal Motor Vehicle Safety Standard
FWD	Front Wheel Drive
G	Germany
GB	Great Britain
GPD	Global Product Development

GRADAP	Graph Definition and Analysis Package
Gs	Gravities
hr	Hours
ID	Identification
IN	India
Int	Integration
IT	Information Technology
J	Japan
kg	Kilograms
km	Kilometers
m	Meters
Manuf	Manufacturing
MDO	Multidisciplinary Design Optimization
Mkt	Marketing
MSDO	Multidisciplinary System Design Optimization
MX	Mexico
N	Newtons
NA	North America
NASA	National Aeronautics and Space Administration
NHTSA	National Highway Traffic Safety Administration
Nom.	Nominal
NVH	Noise and Vibration Harshness
OEM	Original Equipment Manufacturer
P&W	Pratt & Whitney
Param.	Parameters
PCM	Powertrain Control Module
PD	Product Development
PDM	Product Data Management
PDP	Product Development Process
Perfor.	Performance
PLM	Product Lifecycle Management
PM	Program Management
PT	Powertrain
PT Int	Powertrain Integration
QCD	Quality, Cost and Delivery
R&D	Research and Development

rad	Radians
rel.	Relative
SA	South Africa
sec	Seconds
Suppl	Supplier
T	Taiwan
tan	Tangent of an angle
THA	Thailand
TNZ	Team New Zealand
Trans.	Transmission
US	United States
Veh Dyn	Vehicle Dynamics
VPP	Velocity Prediction Programs
w.r.t.	With respect to

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1. INTRODUCTION

During the early years of many of the complex products that we use today (e.g., automobiles, airplanes, computers, etc.), they were usually designed by brilliant individuals who were able to deal with all the technical aspects of the design, develop the manufacturing process and take on the role of the entrepreneur. All the knowledge *"could be stored in the mind of a capable individual."* [2] Also, in the 1950s, in some Western countries, the lack of competition in local markets led to the *"If you build it, they will come"* mindset [32], and therefore there was no need to improve what is called the Quality, Cost and Delivery (QCD) function, which basically seeks better quality, lower costs and shorter delivery times.[11] Unfortunately, this mindset led to inefficiencies in the internal processes of various companies and this was reflected in the way they developed their products.

Starting in the early 1980s, tough competition in the markets (coming mainly from international companies) and rising customer expectations have led companies to focus more on the QCD function; in fact, this trend increases every day. Accordingly, it has become imperative for firms to achieve a set of capabilities that can allow them to compete internationally. Some of these skills are targeted to the design of new products, for it is thought that excelling in Product Development (PD) can provide a powerful competitive advantage.[55] Wheelwright, S. C.; *et al* [55] outlined three mandatory abilities that world-class PD offices should have in today's markets, namely:

1) *Fast and responsive* (speed) which means having shorter development times of better targeted products. This is the result of today's competitive environment as well as the continuous change in customer product expectations. Wheelwright, S. C.; *et al* [55] also attribute the need of this capability to the accelerated technological change we are currently experiencing.

2) *High product development productivity* (efficiency) driven by the variety of products in the market, the growing number of discerning customers and new

process technologies. Under this capability, PD firms must be must be able to increase the number of successful development projects with fewer resources.

3) *Products with Distinction and Integrity* (quality) as a result of demanding customers and saturated markets. This can be achieved with a truly cross-functional development process.

As a consequence of the above imperatives, products have become more complex and more requirements must be incorporated. This makes it impossible for a single engineer to handle all the knowledge required, and specialists in diverse fields must take on the work. However, complex systems typically involve interactions or interdisciplinary couplings, and in many cases it is a challenge to coordinate all efforts to achieve an integrated design. Along with this, time constraints make it impractical to have a sequential design of the diverse areas of the product, resulting in the need for a Concurrent Engineering (CE) process (such as the Multidisciplinary System Design Optimization (MSDO)); the latter basically seeks parallel development of all aspects of a new product. While this has shown to be an opportunity to meet the imperatives mentioned above, there seem to be obstacles to coordination among teams, even in the presence of cutting-edge technologies.

1.1. Objective and Motivation

For effective Concurrent Engineering (or parallel development of engineering systems) to occur, as attempted by the MSDO, the use of high-technology tools is beneficial. However, it also relies on outstanding coordination among teams; [44] this coordination must be in line with the characteristics of the product. Unfortunately, in some PD organizations, this coordination seems to be difficult to achieve, leading to delays in the process.

The motivation of the present work is to eliminate the obstacles precluding the coordination among teams which will permit a more efficient development of a product by easing the CE (in particular, the MSDO which will be discussed in *Chapter* 2). In the case of a company with the latest technologies for PD (e.g., virtual tools), this could represent taking advantage of their full potential. In order to achieve this, it is proposed to perform a comparative analysis of the links among a product's constituents and the organizational ties of its engineers; in the case of an inefficient PDP, some misalignments should become evident. The hypothesis is that if these misalignments are studied, the foundations of coordination inefficiencies among teams can be identified. By understanding their root causes, better approaches can then be taken to enhance a PDP.

1.2. Actual Benefits of Cutting Edge Technologies

In an attempt to enhance their process, some PD firms have made tremendous investments in virtual tools. In fact, Concurrent Engineering relies on them to guarantee the cross-functionality of the Product Development Process (PDP). However, it has been noticed that even the companies with the greatest investments in state-of-the-art technologies are not always the leaders in speed, efficiency and quality. A study from Thomke, S. H. [44] in the automotive industry showed that during the mid-1990s Japanese manufacturers used less sophisticated virtual technologies than their counterparts in Europe and the US (see *Figure 1*). In the case of Computer Aided Engineering (CAE) tools, in the late 1990s, Japanese companies generally had less complex models (in terms of finite elements) than those developed by European and US automotive companies as shown in *Table 1* (refer to *Chapter 3* for further information about different types of virtual technologies). Yet, Western auto manufacturers were outperformed by their Asian counterparts.

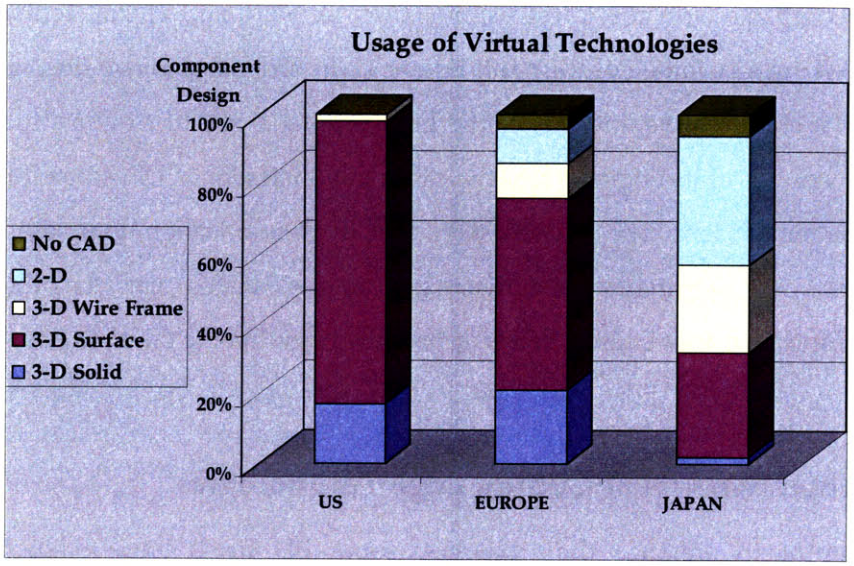

Figure 1. Usage of virtual technologies in the mid-1990s [44]

	Complexity of Simulation Models Used (in thousands of finite elements)		
	US	Europe	Japan
During concept development (for projects completed in the mid- to late 1990s)	55	57	30
During concept development (for ongoing projects)	73	110	111
During design engineering (for projects completed in the mid- to late 1990s)	84	125	48
During design engineering (for ongoing projects)	118	192	115

Table 1. Complexity of CAE models in the global automotive industry [44]

Thomke, S. H. [44] showed the results of a study evaluating the productivity and time to market of Asian and Western auto manufacturers. *Figure 2* shows the utilization of resources in the US, Europe and Japan. The graph shows in the vertical axis, the difference between actual project hours and the expected number for an average project of similar complexity. Therefore, a negative value indicates better than expected whilst a positive value means worse than expected. It clearly shows that, even though Japanese manufacturers possess less sophisticated PD technologies, they showed higher productivity than their counterparts.

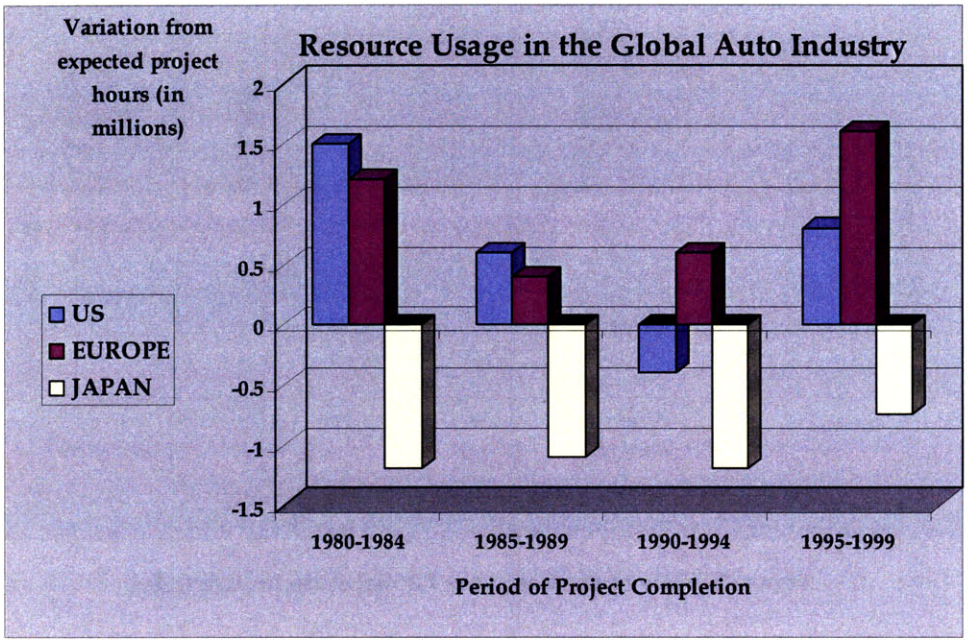

Figure 2. Resource usage in the global automotive industry [44]

Figure 3 shows the comparative time to market for automakers in three different regions. In the vertical axis, the difference between the actual development time and the expected number for an average project of similar complexity is presented. As before, a negative value implies that the manufacturer has a better-than-expected time to market and a positive number means that the company takes longer to launch the product.[44] Clearly, the Japanese automakers outperform Western companies in this regard too.

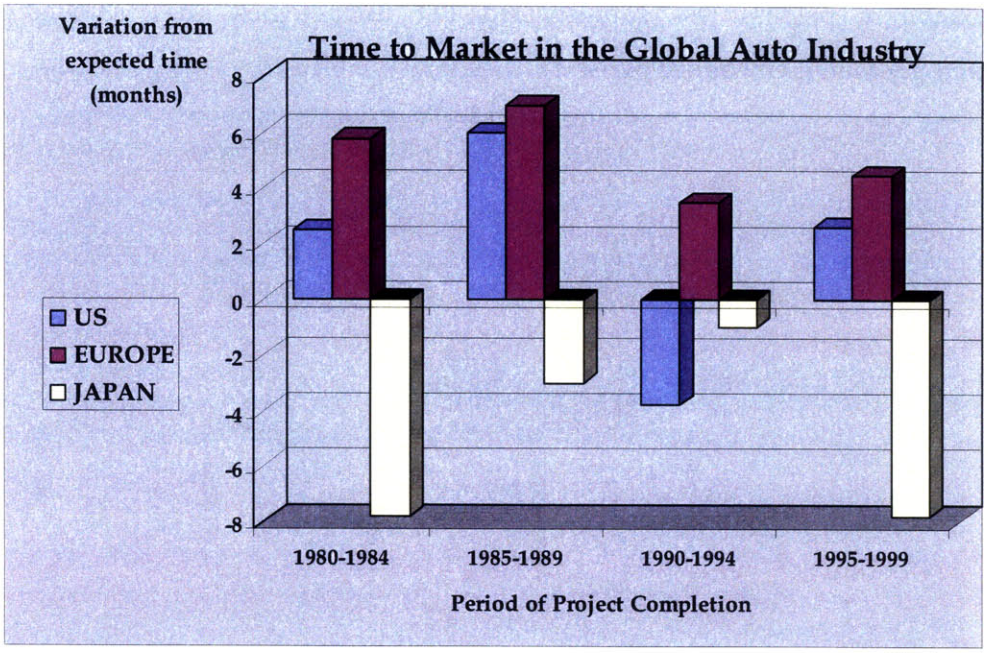

Figure 3. Time to market in the Global Auto Industry [44]

From this and other studies, it appears that state-of-the-art technology, while important, does not guarantee efficient product development. Thomke, S. H. [44] summarizes this with a quote from a manager in his study: *"Even if (a person) had a Ferrari, his daily commute wouldn't be any faster unless he could find a new route that took advantage of the sport car's capabilities. Similarly, a company can't unlock the full potential of leading-edge tools unless it also finds new ways to experiment, learn and manage innovation."* [44] Based on this, there seem to be fundamental factors above and beyond these tools that can obstruct the PDP. One of them may be the organizational element in PD.

1.3. Research Approach

Contrasting with other approaches that have dealt with the product and the organization separately to enhance a PDP, the present research consists of analyzing the product architecture and its social organization in an integrated way. First of all, the product will be decomposed using a CE methodology, namely MSDO, and a set of analytical transfer functions. This decomposition will be transferred to a Design Structure Matrix (DSM) (called N^2 Matrix) from which it will be translated into a network diagram (this diagram will be called *theoretical sociogram*). To determine the strength of the links in the system, a sensitivity analysis of the variables will be conducted. On the other hand, for the organization, surveys will be conducted to identify the interactions of the engineers developing the product at two different phases of the project. With this information, two social network diagrams (one per each phase) will be constructed (these two will be called *actual sociograms*).

The next step will consist of comparing the networks (qualitative analysis) and extracting some measures (namely, degree centrality, closeness and betweenness) from the product and social networks (quantitative analysis) to compare differences in the level of centrality of the systems and engineers of the PD project. Also, with the networks, sociograms will be constructed and compared to identify differences in the ties among actors. Also, additional actors (or intermediaries) in the organizational sociograms should become evident from this study, and the sensitivity analysis of the product will be used to understand their role in the organization.

After the differences have been identified, interviews will be conducted with the main actors of the organization to identify the enablers and obstacles in the transfer of information among teams. Finally, based on literature review, interviews with engineering actors and cases from other companies, recommendations to eliminate the obstacles will be presented with the ultimate purpose of enhancing the PD process. The following diagram summarizes the research approach:

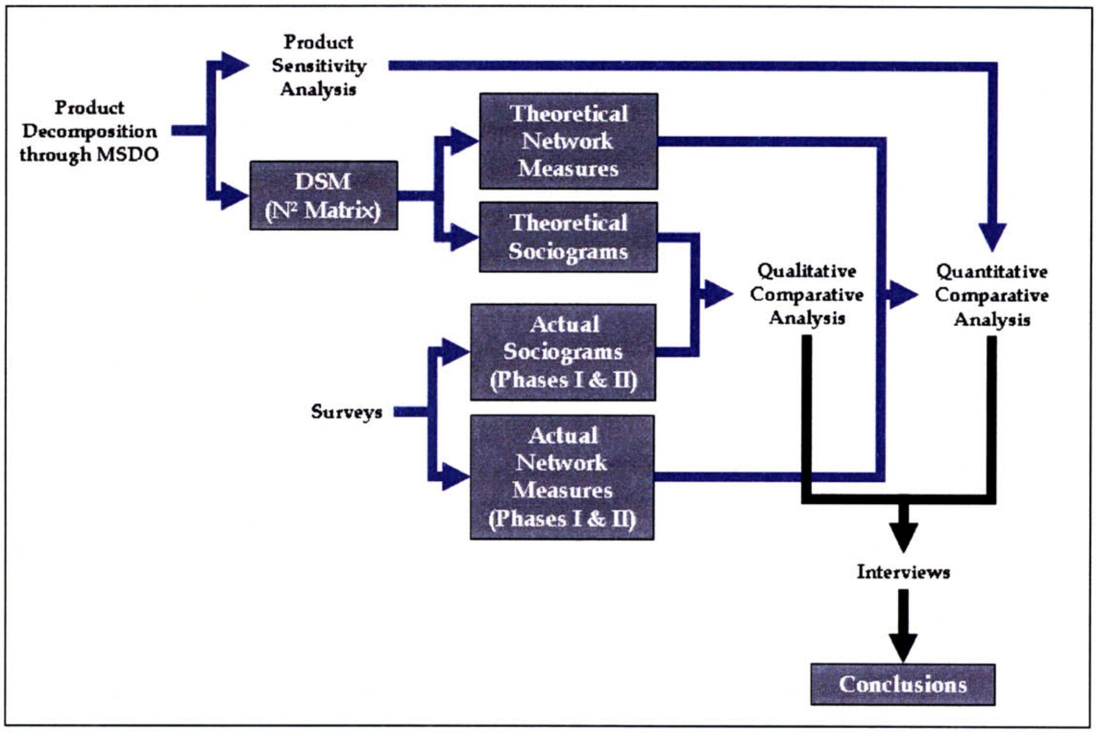

Figure 4. Research Approach

1.4. Structure of the Thesis

The thesis begins with a literature review showing what other authors have done in conducting an integral study of the product and the organization in PD projects. It is followed then by a description of the methods that will be used to conduct the research in both the product architecture and the engineering teams behind it. Subsequently, the methods are applied to a PD team and the results are analyzed; with this, a discussion of the findings takes place. The final sections provide the conclusions of the research including some recommendations to enhance a PDP. Some opportunities for further work in the integrative analysis of technical and organizational systems are described at the end of the thesis (see *Figure 5*).

Figure 5. Thesis Structure

1.5. Final Note

The present document is part of an effort by an automotive manufacturer to enhance its Product Development Processes. Through the integration of the theses developed by its sponsored engineers attending the System Design and Management program, the manufacturer has the goal of becoming a world-class product development center. For other theses developed under this framework, refer to Aguirre Granados, A. [1], Almazan, J.A. [4] and Endo Martínez, V. T. [16].

2. LITERATURE REVIEW

Product Development is a set of interrelated activities requiring contributions from nearly all the functions of a firm, and which begins with the perception of a market opportunity and ends in the production, sale, and delivery of a product. In this regard, a Product Development Process is the sequence of steps that are followed to conceive, design, and commercialize a product.[51] PD has become an important differentiator among companies in today's competitive environment. Being able to get products to market much faster and more efficiently, while still matching the needs and expectations of customers, can provide a significant competitive leverage. Nowadays, doing PD "*well has become a requirement for being a player in the competitive game; doing development extraordinarily well has become a competitive advantage.*" [55]

Because of the importance of an efficient PDP, there have been numerous works trying to find ways to enhance it. This becomes even more critical as the product becomes more complex. While a significant part of a PDP is concerned with the technical aspects of the product, another critical element involves the intellectual and organizational interactions behind it.[1] Therefore, research in this field has dealt, on the one hand, with the arrangement of the technical systems of the product and on the other, with the organizational elements of PD teams.

From a technical perspective, ways to improve the architecture (Arch.) of systems have been widely developed. Generally speaking, architecture can be understood as "*the structure (in terms of components, connections, and constraints) of a product, process or element.*" [28] In the specific case of a product, it deals with the framework by which its functions are allocated to its constituent components.[50] Since the architecture influences several aspects of a PDP (e.g., product change, product variety, component standardization, product performance [50]), several methodologies and tools, such as the DSM, [51] have been used to improve their design. Given that for a product, there

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[1] Other areas important in a PDP include marketing, manufacturing, finance, purchasing, sales, research and development, etc.

are a number of architectures that may satisfy its functional requirements, it is critical to find those configurations that allow for a better PDP.[27]

Organizational studies have also taken place to understand the behaviors of the individuals working in the development of a product. Many of them have performed comparative analyses trying to understand how engineers interact in different companies, industries and countries. For example, Clark, K. B., *et al* [10] outlined some differences in the way engineers from Asian and Western automotive companies share information when solving problem. Other works have identified obstacles that preclude the interactions among engineers such as physical and organizational barriers (Allen, T. J., *et al* [3]).

Studying the architecture of a product and its organization separately has provided improvements in PDP. However, when dealing with complex engineering systems, the technical and organizational dimensions are not separate entities; they depend on each other. Therefore, studying them with a more integrative approach can provide interesting insights about the process. By analyzing the similarities and differences between the technical and organizational settings in a PDP, new areas for improvement can become evident. In this section, some previous works under this integrative approach are described.

2.1. Product Adapted to the Organization

MacCormack, A.; *et al* [27] performed a study in the design of complex software where he discusses some its architectural aspects and how they could have been influenced by some organizational factors. The reason they chose to analyze software was because it provided them with some advantages: First, the code could be processed automatically to clearly identify its internal dependencies; second, due to the sophisticated version-control used by software developers, it was possible to easily track the evolution of the design. In this research, the architectures of three software products were compared: the Linux operating system and the Mozilla Web browser. The former is open source software; for the latter, two versions were studied, one representing the result of a proprietary development and the other, an open source architecture. This is important to highlight because open source software is characterized by highly distributed volunteer developers who contributed to the code; on the other hand, proprietary development of software is done by dedicated teams of individuals who are in a single location and can have easy interaction among them.[27] The hypothesis was that depending on the organizational setting of its developers, a higher or lower level of modularity might have been required in the internal architecture of the software.

To perform the analysis, MacCormack, A.; *et al* [27] used the DSM. With this, they defined two metrics to measure the degree of modularity of a design based on the examination of the costs of dependencies between the elements of the DSM.[2] The first metric was the *propagation cost,* which assumes that all the dependencies between elements, both direct and indirect, incur the same cost regardless of either their location or the length of the path between them. This metric is composed by the "fan-out visibility" and the "fan-in visibility"; an element with high fan-out visibility depends on many other elements, whilst an element with high fan-in visibility has many other elements depending on it.

The second metric was the *clustered cost,* which assumes that the cost of dependencies between elements will differ depending on whether elements are in the same or different clusters. Those in the same cluster are assumed to incur a low cost; those between clusters, are assumed to incur a high cost. With these two metrics in mind, the degree of modularity of the software under analysis was identified. The study appears to indicate that Linux and the open-source version of Mozilla, are more modular than the proprietary version of Mozilla. This could be indicative that, because of the dispersed location of the developers, it would make more sense to have more modular code; on the other hand, a proprietary version might require less modularity because face-to-face interactions are easier to achieve.

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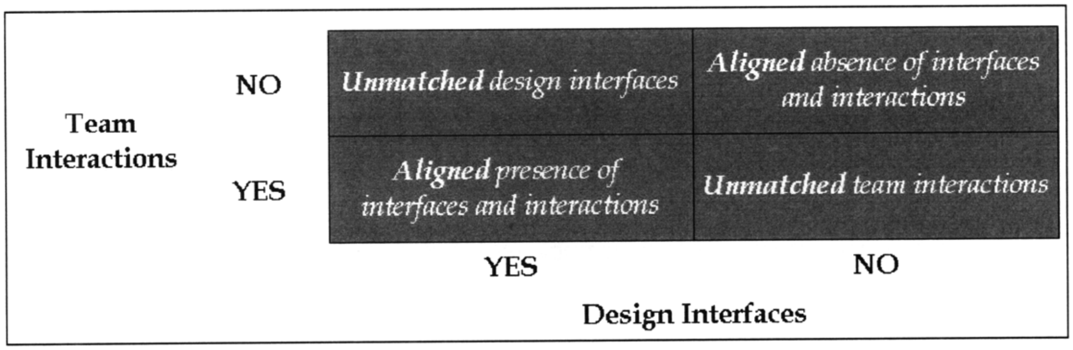
[2] In the study, it was argued that the degree of modularity of a system must be measured comparatively; i.e., it can only be said that a product *A* is more (or less) modular than product *B*.[27]

The research by MacCormack, A.; *et al* [27] provided some insights about the idea that a product's design could mirror the organization that develops it. However, the analysis was performed more from the point of view of the product itself, while a more qualitative description was provided about the organization. A way to incorporate some quantitative data from the organizational side could have provided more insights. In addition, an extension of this research could be to perform it in physical products (such as a vehicle or an airplane) that do not show the benefits of the software.

2.2. Map of Design Interfaces and Team Interactions

Complementing the research of MacCormack, A.; *et al* [27], in the paper of Sosa, M. E.; *et al* [38], they performed a study in a product development project integrating the product architecture and organizational structure. Two terms were defined: 1) *design interface* in which one component *i* of a product depends on component *j* for functionality; 2) *team interaction* in which design team *i* requests technical information from team *j*. The former is used for the product architecture and the latter, for the organization. When comparing the design interfaces of the product with its respective team interactions, Sosa, M. E.; *et al* [38] makes an interesting mapping describing four potential combinations that may occur, as shown in *Figure 6*:



Team Interactions	Design Interfaces: YES	Design Interfaces: NO
NO	***Unmatched*** *design interfaces*	***Aligned*** *absence of interfaces and interactions*
YES	***Aligned*** *presence of interfaces and interactions*	***Unmatched*** *team interactions*

Figure 6. Map of design interfaces and team interactions

The study proposes six hypotheses related to the four combinations above. To confirm them, the authors studied the design of a Pratt & Whitney (P&W) commercial aircraft engine. Their approach consisted first of identifying the design interfaces of the product by interviewing experts; this allowed them to understand how the decomposition of the system could be performed. With this information, a *design interface matrix* using a DSM was generated, identifying how components were interrelated; also, interfaces were categorized as *Weak* or *Strong* to define the criticality of each tie. The second step was the identification of team interactions through surveys to key members of each team; with this, a second table capturing the interrelations of the team was created and called *team interaction matrix*. As before, it was based on a DSM.

Once the design interfaces and team interaction matrices had been created, both dimensions, the product and the organization, were in an environment where they could be compared. With this information, a new matrix, the *alignment matrix*, was created from the overlay of the previous DSMs. The final step in Sosa, M. E.; *et al* [38] was to analyze this last matrix using statistical network analysis techniques to test the hypothesis (namely, *log-linear* p_1 and *logit* p^*).

With the approach in the study, interesting conclusions were observed regarding similarities and differences among the ties of a product's constituents and the teams developing them, at least for the project under study. First of all, misalignments between interfaces and interactions tend to occur in the cross-functional boundaries. However, if the design interface is stronger, the probability of having the respective teams interacting is high. Another important conclusion was that it seems that a direct design interface tends not to be replicated in the organization in the presence of intermediaries.

2.3. Contribution of the Present Work

Complementing the study of MacCormack, A.; *et al* [27], and similar to Sosa, M. E.; *et al* [38], the present work attempts to analyze both, the technical and organizational dimensions of a product development project to understand its enablers and obstacles. Deviating from the latter, a method used in social sciences, namely Social Network Analysis, is proposed to compare the technical and the social elements. Just like Sosa, M. E.; *et al* [38], surveys will be conducted to establish the interactions of the organization. However, this step will be performed for two phases of a PD project trying to identify any evolution of the interactions with the time.

On the other hand, a DSM of the product will be generated using as a reference the MSDO methodology, but rather than by interviews as in the case of Sosa, M. E.; *et al* [38], analytical transfer functions will be used for its construction. The intention of this is to eliminate any potential bias in the definition of the product's interfaces. Also, analogous to the *Weak* and *Strong* criteria [38], a sensitivity analysis following, again, the MSDO methodology will be performed to achieve a more quantitative criteria of the strength among design variables.

Rather than having the product and the organization in matrices, both, the DSM and the survey results, will be translated into social network diagrams to have them in the same comparative platform. With this, statistical measures from the social network theory will be used to quantitatively describe the technical and social networks. These measures will try to describe the centrality of the actors; in fact, these measures are quite similar to the fan-out and fan-in visibility discussed by MacCormack, A.; *et al* [27]. The purpose of this approach is to understand why elements that might be central to the product, are not so in the organization. This will also provide an understanding of the benefits or detriments of intermediaries.

3. METHODS FOR THE ANALYSIS OF ENGINEERING SYSTEMS

The purpose of this chapter is to introduce some methods to analyze engineering systems. A complex engineering system not only consists of a technological part, but also of management or societal interactions.[18] Therefore, tools to analyze 1) the technical elements of a product and 2) the organization behind its development are needed. Besides, a way to compare or contrast these two dimensions is fundamental to understand if there's coherence among them.

For the analysis of technical systems, a number of methods are available. One of the most widely developed, and which will be used in the present work, is the MSDO methodology as explained by The American Institute of Aeronautics and Astronautics (AIAA), 1991 [2]. The MSDO, as will be shown, provides a way to decompose and optimize a technical system, as well as to determine the sensitivity among its constituents.[42] Also, the way the information is structured will allow for the creation of interdependency maps or network diagrams showing the internal links among the product's systems (this will be referred to as "theoretical sociograms").

On the other hand, to study an organization, a method to assess its social capital based on social networks will be presented. Through the construction of network diagrams and the extraction of some metrics, enablers and/or obstacles for social interaction should become evident (this will lead to the creation of what will be called "actual sociograms"). Finally, having both, the technical and the social part in a common platform of communication (i.e., network diagrams) a way to compare the organizational behaviors and the architecture of a product will be introduced.

3.1. Multidisciplinary Design Optimization and the Early Learning

Being able to capture the value of the synergies of the interdisciplinary couplings while allowing a parallel design process is where the value of CE resides. Within CE there is a specialty field called Multidisciplinary Design Optimization (MDO) that attempts to formalize the search for optimal configurations in the presence of strong interactions amongst disciplines (i.e., cross-functionality in the development process).[13] The main strategy of MDO is to prompt learning about a given design as early as possible in the PDP while maintaining design flexibility for a longer time. The argument is that as a design evolves, engineers tend to learn more but at the same time, they become more limited in their ability to perform any changes to improve it; the result is a suboptimal design.[2] Increasing the time to understand the design, and being able to perform the required changes for a longer period of time, should allow the development of more optimal alternatives. This can lead to more efficient designs, with fewer amounts of resources.

The AIAA, 1991 [2] provides a couple of diagrams depicting the divergence between knowledge gain and design freedom in the design of an aircraft. In ***Error! Reference source not found.****Figure 7*, as well as in *Figure 8*, three phases are used to summarize the PDP. The first phase is the conceptual design, which, in the case of an aircraft, deals with the initial concepts in the field of Aerodynamics (Aero) and Propulsion. The second phase is called preliminary design, and it is where the structural portion of the aircraft is developed. Last but not least, there is the detailed design phase where the aircraft control systems are refined. Crossing these phases, two lines are shown, one for the evolution of the *Design Freedom* (brown curve) and the second for the evolution of the *Knowledge about the design* (green curve). Also, each phase shows a set of bars which indicate how the efforts are distributed in each phase.

Figure 7 represents the traditional approach. First of all, it displays a short conceptual phase in terms of timing, which translates to a rapid decrease in design freedom. In addition, the bars indicate that the distribution of efforts is unequal, showing more concentration on Aerodynamics and Propulsion than on the rest. Consequently, the learning potential is limited and the opportunity to make integrated improvements and changes as provided by the design freedom is diminished. Reinforcing this, as the design evolves from one phase to the next, the resources are shifted, resulting in unbalanced progress of the systems; this contributes to the delay in the learning process, and by the time a good understanding is achieved, most of the product design is already frozen.

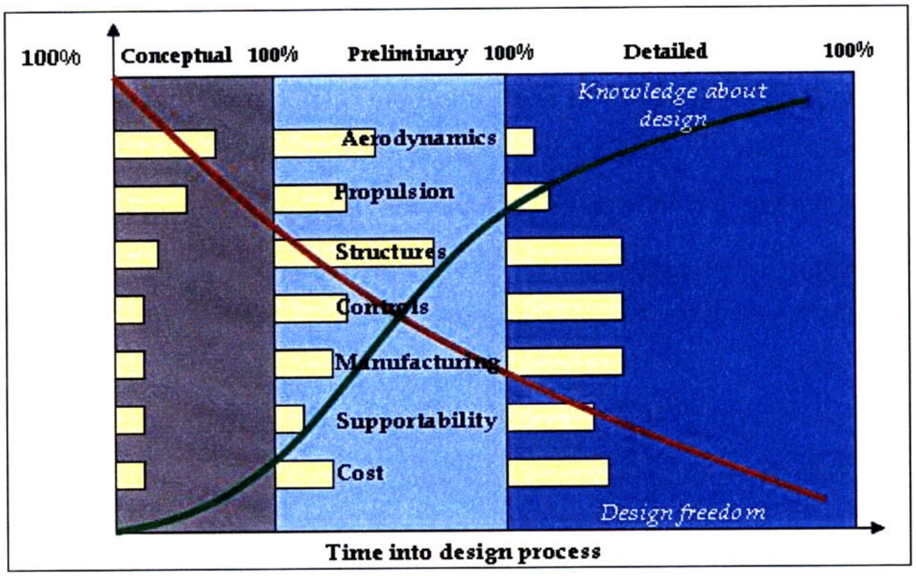


Figure 7. Knowledge and design freedom in a PDP: traditional approach [2]

On the other hand, *Figure 8* shows the approach provided by MDO. The first feature that can be highlighted is that the three phases are distributed evenly throughout the timing of the PDP. Increasing the timing of the conceptual phase delays the design freedom decay and gives engineers design flexibility for a longer period of time (see the dotted brown curve). Along with this, the resources assigned to the various fields are distributed more evenly as contrasted with the traditional approach, allowing systems to be developed in parallel. This drives a shift to the left in the learning curve (see the dotted green curve), meaning that the understanding of the overall product occurs much faster in the PDP. The combination of ramping up the learning curve while being able to change the systems for a longer period of time allows more optimal designs and improvement of the QCD function.

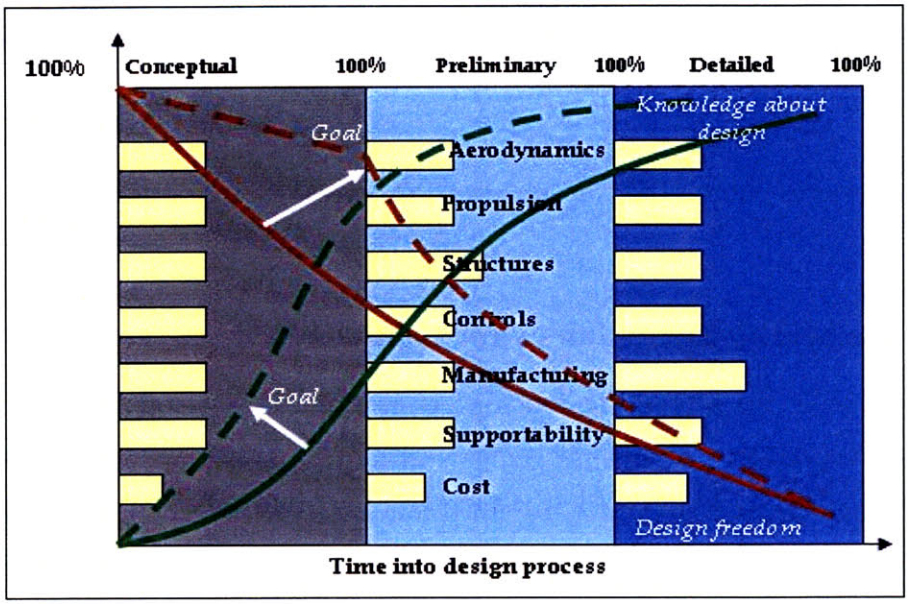


Figure 8. Knowledge and design freedom in a PDP: MDO approach [2]

The MDO approach shows a very efficient way of conducting a PDP; nonetheless, given the complexity of today's products and the amount of couplings they present, it becomes challenging to have a parallelization of the design process (i.e., different areas progressing at a similar rate) and at the same time have the proper cross-functional interactions occurring. In order to achieve this, MDO focuses on a more integrated product design based on two main areas:

1) A structured process for information sharing so that any development can be cascaded promptly to the affected areas. By doing this, all the teams with a stake in the design can keep abreast of its evolution. This area is critical in any PDP, not only because it speeds it up with fewer flaws, but also because it sets the foundations for an efficient innovation process.[3]

2) A structured process so that in the presence of any design change, it can be evaluated by the proper stakeholders to guide the design towards a more optimal result.[2] Besides, as described by Thomke, Stefan, 2003 [46] the learning process is more efficient if a design proposal is followed by immediate feedback achieved by experimentation. Consequently, in this process, frequent

experimentation must take place to foster a better understanding of the systems much faster.

With these pieces put together, an enhanced PD process should be achieved.

3.2. The MSDO Methodology for Complex Systems

The objective of the MSDO methodology is intended to develop optimized complex systems that need to meet diverse goals which in many cases appear to be in conflict. MSDO is a generalization of MDO, applied to complex systems. This methodology has proven to be very effective in different fields such as in the aero and astronautics, civil engineering and automotive industries, to name a few. For example, Wakayama, 2000 [53] provides an interesting example on how MDO was applied in the design of a new Blended-Wing-Body (BWB) aircraft. It shows how it was possible to correct some balance problems encountered in previous versions of the BWB while still improving the takeoff weight.

While the way various researchers use the MDO approach may show some minor differences, the AIAA, 1991 [2] has developed a framework that generalizes how an MDO endeavor should be carried. From the work of de Weck and Wilcox [14] and Papalambros, *et al* [36], the following steps and nomenclature can be outlined:

1) Definition of the systems' boundary which isolates it from its environment. Anything crossing the boundary can be considered either an input or an output which characterize the system.

2) Definition of the systems requirements which are the needs that a system must fulfill. These are usually implemented as inequality or equality constraints in the subsequent implementation.

3) Identification of objectives which are the criteria used to describe an optimal design. These are the responses of the systems that are attempted to be

maximized or minimized. They are usually a function of the design variables (see next bullet) and are grouped in the *Objective Vector* **J(x)**.

4) Definition of the design variables which are the quantities within the domain that describe the different states of the systems. The values these variables take must be within a feasible range and are typically grouped in what is called the *Design Vector* **x**. The design vector is the embodiment of the designers' freedom to choose.

5) Determination of constraints which are terms expressed as functions of the design variables and which **must** be complied by any feasible design due to technological and economic limitations among others. In general, two types of constraints can be described: inequality constraints expressed as $\mathbf{g(x)} \leq \mathbf{0}$, and equality constraints $\mathbf{h(x)} = \mathbf{0}$.

6) Identification of parameters which are fixed quantities given by, either the architecture of the systems or by natural phenomena.[3] They are grouped in the *Parameter Vector* **p(x)**.

7) Decomposition of the system in modules which are a set of coupled mathematical relationships which, given an independent input, provide dependent outputs. Typically, each module is handled by a specific team in an organization and may represent a "black box" to other teams (see *Figure* 9).[14]

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[3] Some texts (e.g., Papalambros, *et al*, [36]) may differentiate the architectural fixed quantities from those relative to the natural phenomena (e.g., gravity, air's density, etc.) by calling them *parameters* and *constants*, respectively.

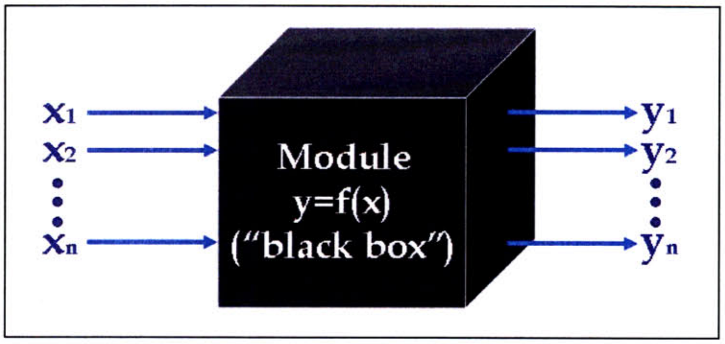

Figure 9. Graphical representation of a module

8) Development of the governing equations (*y=f(x)*) of each module. In various industries, these functions, more than mathematical expressions, can be numerical models or even physical prototypes describing the behavior of the systems. These representations are critical to evaluate the functions and conduct the optimization of a product (a brief description of some of the tools used for this purpose is presented in sections *3.2.1*, *3.2.2* and *3.2.3*).

9) Integration of the modules via systems engineering tools (e.g., *N^2 diagram* introduced in *Chapter* 4) to simulate the overall behavior of the product.

10) If available, comparison of the model with respect to surrogate systems.

11) Identification of the most relevant design variables to perform the optimization.

12) Optimization of the model to minimize or maximize the given objectives.

13) Post-processing of the results to evaluate both, the sensitivity of the model with respect to relevant variables, and the trade-offs to be performed.

The steps presented above will be followed in the design of a set of coupled vehicle systems / attributes in the coming sections.

3.2.1. *Verification and Validation Tools*

When using the MSDO, it is important to understand some of the tools available to optimize a product. Evaluating a design at different stages prior its release to the market is a fundamental task in any PDP. Thomke, Stefan H. [46] refers to this process as experimentation and it is critical to create the early knowledge about the new product attempted by the MDO, which leads to its development and improvement. Unfortunately, experimenting with physical prototypes is expensive due to the time and labor required to build them; therefore, the use of mathematical models is currently a standard practice in a great variety of industries (e.g., automotive, aerospace, electronics, etc.).

Attempting to describe complex systems through accurate mathematical equations is not practical in many industries. Thanks to the steady decrease of computational cost, the increase in the capacity of integrated circuits (Moore's Law states from empirical observations that the number of components per chip doubles every two years) and the availability of supercomputers and cluster-based computers, the use of numerical representations through computer models is the approach taken by PD offices around the world.[52] A. Brenner [7] provides a graph describing the growth of computer technology since 1955 in terms of millions of operations per second. Presented in *Figure 10,* it indicates on the top several milestones related to the evolution of IT systems; in addition, two curves are shown: The upper describes the leading-edge products, and the lower is related to functional / affordable computer systems (products in parenthesis are not considered leading edge).[4] Finally, problems that are solved in a reasonable amount of time are illustrated in brackets. It can be observed how complex problems related to weather predictions and structural biology can now be computed with IT systems.

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[4] Approximate prices in the graph are shown in dollars at the time.

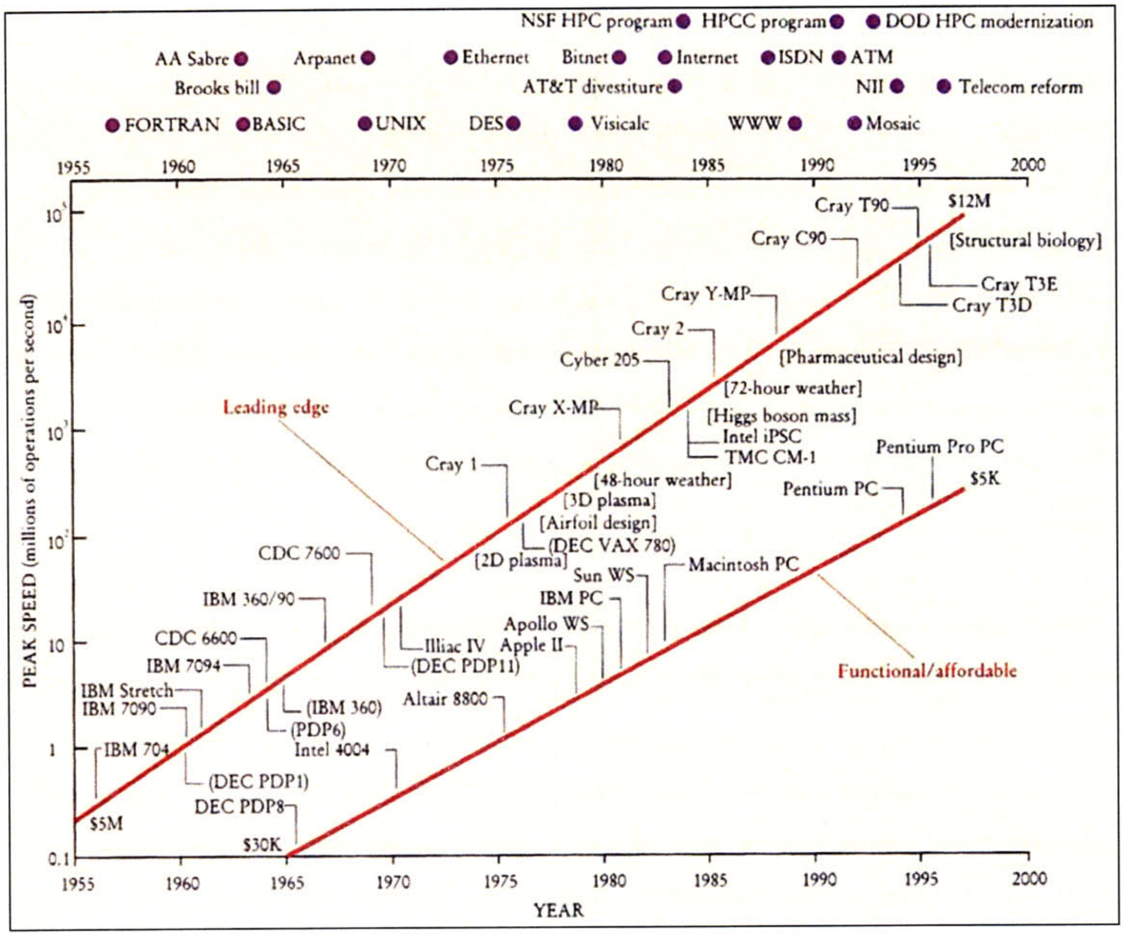


Figure 10. Evolution of computer simulation [7]

Different types of virtual tools are now available to evaluate (or experiment with) the behavior of systems, including: [46]

- Computer-Aided Styling (CAS): allows designers to visualize computer models from different perspectives, with the ability of performing modifications at any point of the geometry. A couple of CAS applications are *Godzilla* [41] and *Alias | Wavefront's AutoStudio*.[9]

- Computer-Aided Design (CAD): permits representation of geometries such as 2-D, 3-D solids and surface models. Software like *AutoCAD, Unigraphics, Catia* and *Pro/Engineer* are widely used.

- Computer-Aided Engineering (CAE), which supports engineers in the analysis, simulation and prediction of systems' behavior (e.g., stresses, frequencies, deformation, displacements). These tools are typically based on numerical methods such as the Finite Element Method (FEM) (also referred to as Finite Element Analysis (FEA)) and Multibody Dynamics. Three steps are needed to conduct a CAE analysis, namely:

    1) *Pre-processing,* where the geometry is imported from a CAD system and is used to generate the mesh (or finite elements) of the parts under study. The material properties and gauges are defined and finally, the boundary conditions (loads, predefined displacements, constraints, etc.) are established. Software used in the pre-processing phase includes Altair's *Hypermesh* and *Hypercrash, LS Pre-Processor* by Livermore Software Technology Corp., etc.

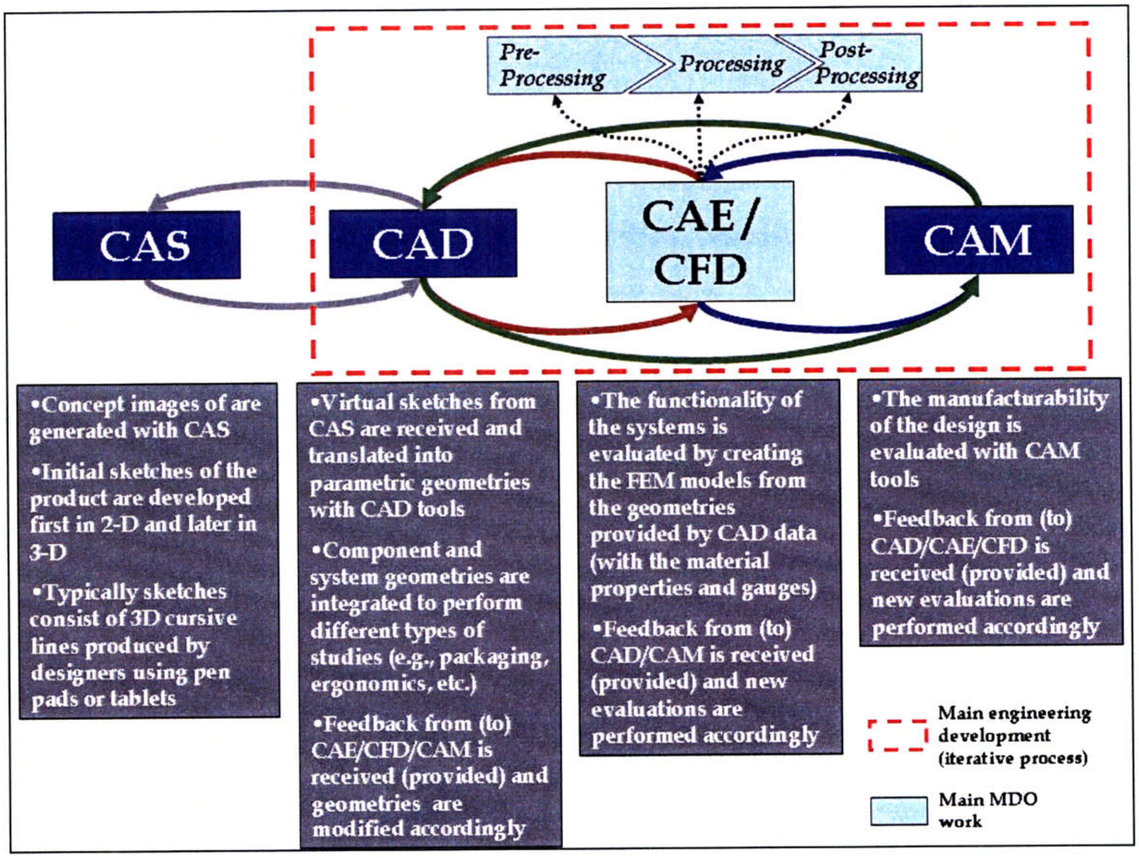
    2) *Processing,* where the equations and numerical methods are solved. This is the most demanding phase of the CAE analysis, in terms of computing, and is usually performed by supercomputers and/or clustered computers. A wide variety of products are used depending on the application, including *MSC Nastran* by MSC Software (for structural and frequency analyses), Adams (for multibody dynamics), *LS-Dyna* by Livermore Software Technology Corp. and *Radioss* (both for time dependent studies), *Abaqus* by SIMULIA of Dassault Systèmes (for multipurpose analysis), etc.

    3) *Post-processing,* where the results are analyzed through plots, animations, contour graphs, deformed shapes, etc. Altair's *Motionview* and *Hypergraph,* Livermore's *LS-Post, Ensight* among others, are used as post-processors.

- Computational Fluid Dynamics (CFD): similar to CAE but is used for thermal and fluid flow analyses (Finite Difference-based models are developed with CFD tools). *Fluent* by Fluent Inc. and *Star-CD* by CD-adapco are good examples of processors for this type of analyses.

- Computer-Aided Manufacturing (CAM), which helps engineers to simulate manufacturing and prototyping processes. Examples include *Autoform*, *Pam-Stamp* and *Mastercam*.

The flow chart in *Figure 11* summarizes how these technologies are typically used in a PDP. It is worth mentioning that these tools are critical to develop a product; however, MDO mainly relies on CAE and CFD.



- Concept images of are generated with CAS
- Initial sketches of the product are developed first in 2-D and later in 3-D
- Typically sketches consist of 3D cursive lines produced by designers using pen pads or tablets

- Virtual sketches from CAS are received and translated into parametric geometries with CAD tools
- Component and system geometries are integrated to perform different types of studies (e.g., packaging, ergonomics, etc.)
- Feedback from (to) CAE/CFD/CAM is received (provided) and geometries are modified accordingly

- The functionality of the systems is evaluated by creating the FEM models from the geometries provided by CAD data (with the material properties and gauges)
- Feedback from (to) CAD/CAM is received (provided) and new evaluations are performed accordingly

- The manufacturability of the design is evaluated with CAM tools
- Feedback from (to) CAD/CAE/CFD is received (provided) and new evaluations are performed accordingly

Figure 11. Summary of virtual tools used in PDP

Unfortunately, certain phenomena are still difficult to predict using virtual tools (fracture propagation, for instance), and therefore, physical prototypes are still required to evaluate (and even to optimize) the design with more certainty. For example, Thomke, S. and Bell, D., 2001 [47] developed the Economic Testing Frequency (ETF), which represents the optimal number of tests to be conducted in the development of a product. While this number depends on several factors, a rough estimate is the following expression:

$$Number\_of\_test\_rounds = \sqrt{\frac{ac}{tc}} \qquad \textbf{Equation 1}$$

where ac is the avoidable cost if continuous testing found problems without any delay, and tc is the cost of one round of tests.

3.2.2. *Combination of Virtual and Physical Evaluation Tools*

In practice, many industries make use of a combination of numerical simulations and physical tests to evaluate the performance of their products at an integrated, systems and component levels. For example, typically, computer analysts need information from physical tests to correlate their models as well as to complement them with relevant information coming out from tests. As mentioned before, since there are still some behaviors that are difficult to predict using computer applications, this step is critical to develop reliable models.

On the other hand, test engineers also need feedback from computer analysts to conduct there tests more efficiently. With the predictions of CAE or CFD models, the preparation of physical prototypes can be performed in such a way that more relevant information can be obtained. CAE, for example, can provide guidance about the proper location of some instrumentation channels (accelerometers, thermocouples, pressure sensors, cameras, to name a few) based on the critical areas observed in the computer models. Also, since changes in the design are much easier and less expensive to evaluate with computer applications, they can provide direction about ways to build up or modify a prototype to make sure it represents the intended behavior of the design (addition of reinforcements, geometry changes, removal of parts, for instance).

Thomke, Stefan, 2001 [45] explains that by combining what he calls "traditional" and "new" experimentation technologies (e.g., physical prototyping and virtual tools, respectively) an efficient verification process can be achieved. In *Figure 12*, these benefits are captured in a *Technical Performance vs. Effort* plot;[5] first of all, the "Traditional only" curve indicates the performance that can be achieved with just physical testing. On the other hand, with computer technologies ("New only" curve), about 70% to 80% of the total technical performance is achieved in much less time and cost, showing significant savings from a traditional PDP. Unfortunately, due to limitations in the virtual models, the remaining 30% to 20% can't be achieved and a performance gap with respect to traditional technologies appears. Nevertheless, there is a "switching point" which occurs when the slope of the "new" and "traditional" curves is the same and it is where both approaches should be integrated. With this integration, the performance gap is eliminated and could also lead to increased innovation (shaded area).

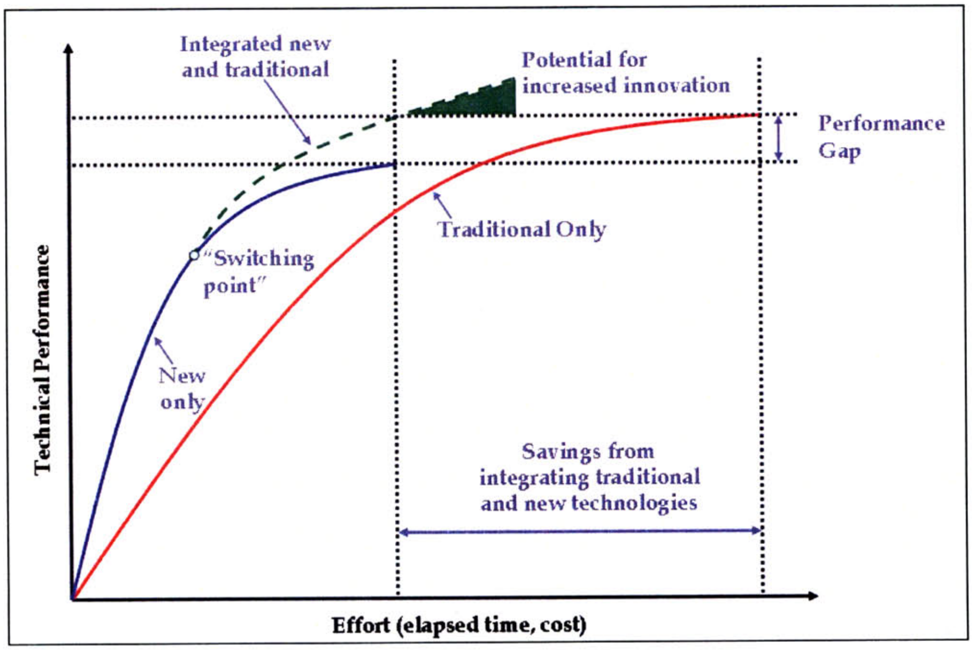


Figure 12. Benefits integrating new and traditional experimentation tools [45]

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[5] Effort is expressed in terms of elapsed time and cost.

3.2.3. *Integration Tools for Optimization*

Several tools have been developed to conduct the optimization of systems. These *optimizers* are basically intended to integrate the results from CAE/CFD/CAM models or, in some cases, even physical tests to conduct the optimization process. Using different types of iterative algorithms (i.e., deterministic or stochastic) they use the information from previous iterations to determine the subsequent evaluations (see *Figure 13*). Some of these applications include Esteco's *ModeFrontier* (based on Genetic Algorithms), *Isight* and *ModelCenter*. Ideally, these applications are able to handle models from different applications or software to optimize diverse functions of a product (e.g., thermal, stresses, stamping and frequencies).

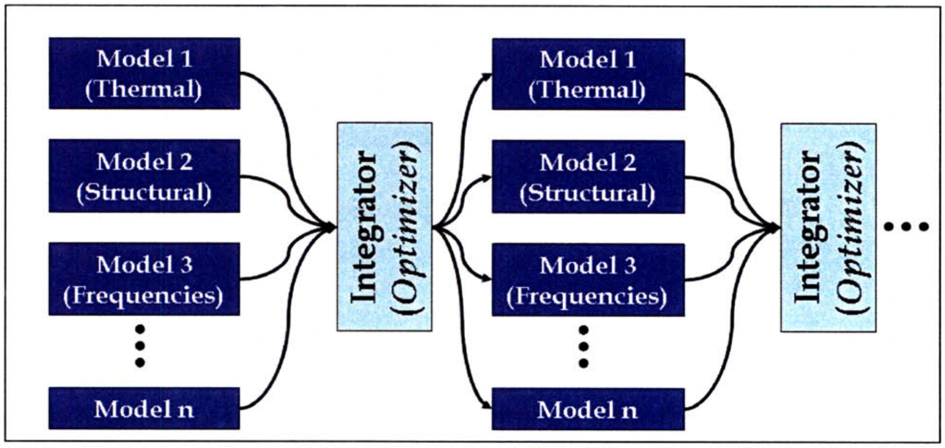

Figure 13. Ideal optimization process using integration tools or optimizers

A summary of the different methods for system verification or experimentation as well as optimization methods is provided by Law, et al, 1999 [26] (later modified by M.J. Steele). *Figure 14* basically shows how a system can be evaluated by means of physical tests or mathematical models; the latter is divided into different tools that can range from analytical equations to numerical solutions.

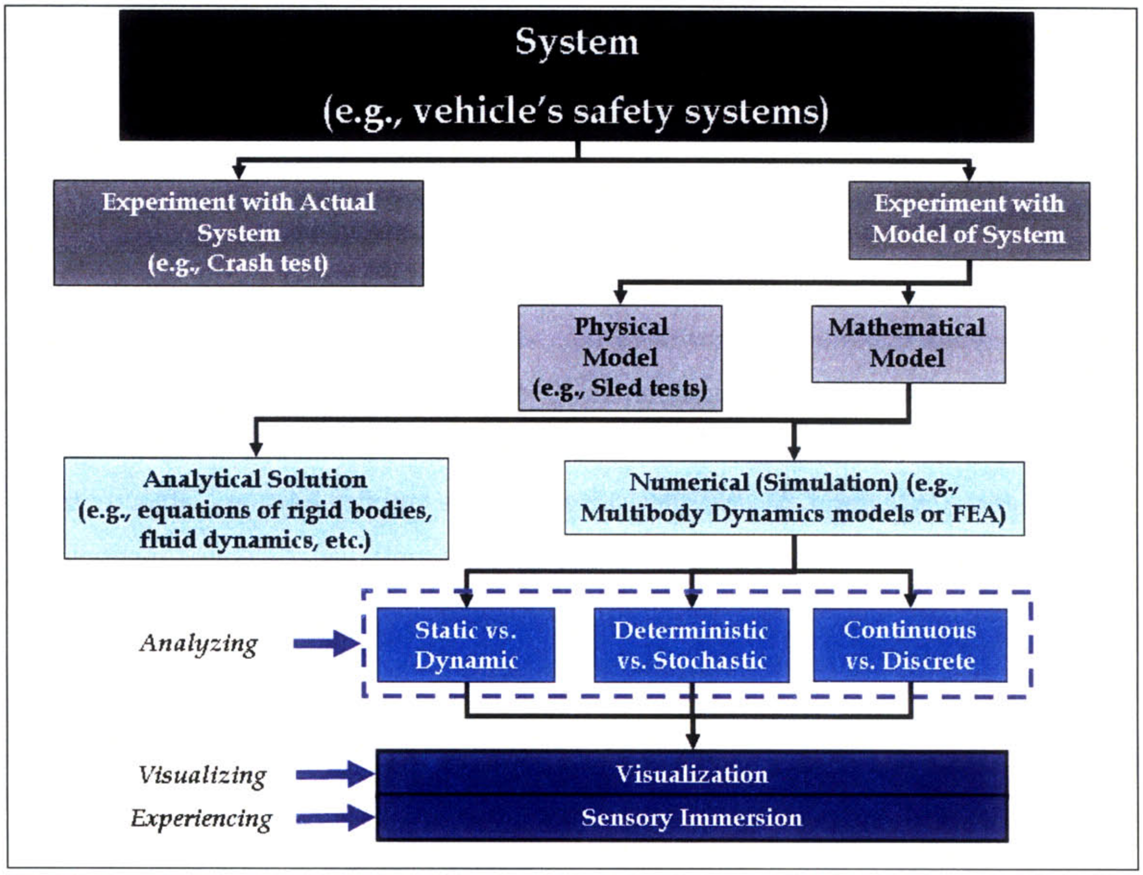

Figure 14. Decomposition of experimentation methods [7]

3.3. Social Capital in Organizations and MSDO

In the previous section, a way to analyze a set of interrelated systems using MSDO methodology was presented. The steps of the MDO provide a structured way to handle complex systems from a technical standpoint; however, in practice, the development of complex systems is performed by different engineering groups and "*one of the central issues in the effective management of development is the linking of knowledge and information held in different departments and functions.*"[10] Therefore, in order to achieve the multi-objective optimization of a system, organizational factors should also be considered.

Nowadays a great part of the information a PD organization deals with is handled using Information Technology (IT) systems such as Product Data and Lifecycle Management (PDM/PLM) applications. These virtual frameworks have evolved up to a level that allow management of all the data generated during the development of a product including the concept generation, design and manufacturing processes.[23] Nonetheless, in some PD teams, the more complex a design becomes, the less information is properly stored. In fact, a study conducted by Dong, 1999 [15] in an automotive Original Equipment Manufacturer (OEM) showed how in the design of an engine's throttle body, most of the system level knowledge was kept in experienced individuals rather than in formal documents (see *Figure 15*). Being able to extract this information becomes important to optimize a product.

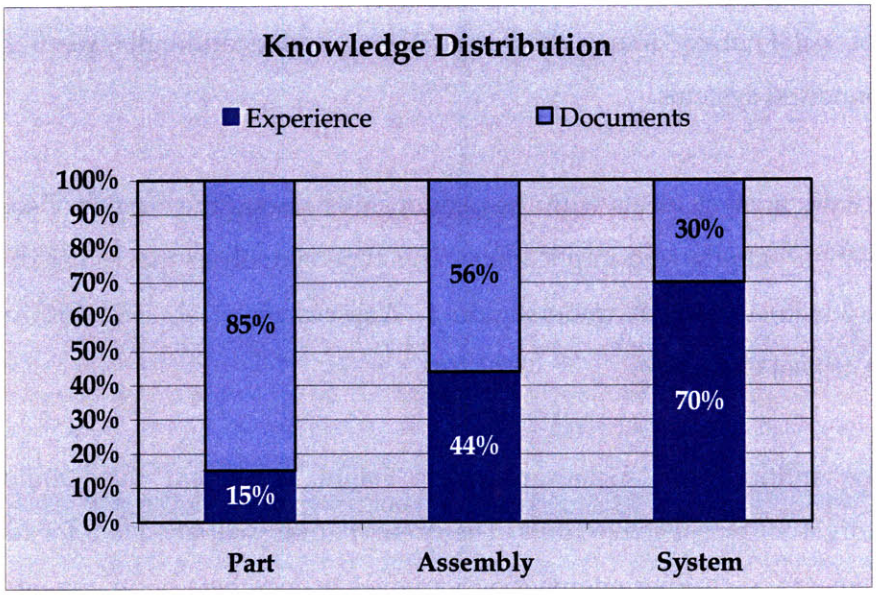

Figure 15. Where was the knowledge of the throttle body design [15]

There are two terms that are worth clarifying at this point to understand the importance of social interactions when optimizing a multi-objective problem. The first is *human capital* which refers to what an individual knows, i.e., the sum of his or her own knowledge and abilities. On the other hand, *social capital* refers to the resources available due to the interactions between the members of an organization. Baker, 2000 [5] mentions that human capital refers to what an individual knows, while social capital depends on who an individual knows (or doesn't know). The argument of the present study is that the MSDO methodology *per se* is an effective tool when a single individual has knowledge of all the variables involved in a product (human capital). Nevertheless, in a PD organization where numerous teams are responsible for the different portions of the system, and the knowledge is scattered throughout all its members, understanding how to enhance the social capital becomes important too.

3.4. Basics of Social Network Analysis

3.4.1. *Elements of Social Networks*

Elements from the field of Structural Analysis in the Social Sciences can be used to evaluate, build, and use the social capital within a group. In particular, tools used in the analysis of social networks may allow for a deeper understanding between the elements of interconnected systems.

Social network analysis deals with the relationships among the entities of social groups, as well as their patterns and implications. This type of analysis makes use of a few basic elements which are worth understanding. Wasserman, *et al*, 1994 [54] outlines the following critical elements:

1) The entities of a social group are called *actors* and they could represent individual or collective units. The present study will always refer to individual elements (i.e., either engineering variables or members of an engineering team). It is worth mentioning that all the actors on which measurements are taken are typically known as an *actor set.*

2) The linkage between a pair of actors of a social group is referred to as a *relational tie.* These ties may represent different types of connections between actors including, but not limited to transference of resources, affiliations, behavioral interactions or physical connection. For the analysis of the engineering system, the *relational ties* should be understood as a transference of information between the variables of the system (for the analysis of social interactions presented in *Chapter 4,* ties will represent behavioral interactions). Also, the collection of ties of a specific kind is called a *relation.*

3) The basic unit of study of a social network is called a *dyad* which is made up of a pair of actors potentially connected by relational ties. The connection among a greater number of actors is also relevant for study such as *triads*, which are three actors potentially tied among them (see *Figure 16*).

4) A subset of actors and the ties among them is called a *subgroup*. Wasserman, *et al*, 1994 also defines a *group*, which "is the collection of all actors on which ties are to be measured;" however, since a single engineering project (or a single engineering organization) will be analyzed, the terms *actor set* and *group* will be interchangeably used.

5) Actors of a network that are able to connect diverse groups are called *linchpins* and they typically serve as shortcuts for the information flow. *Linchpins* are critical in Social Sciences because they are able to convert a big and disconnected "world" into a small one.[5]

All the elements listed above integrate a social network, which basically *"consists of a finite set or sets of actors and the relation or relations defined on them."*[54]

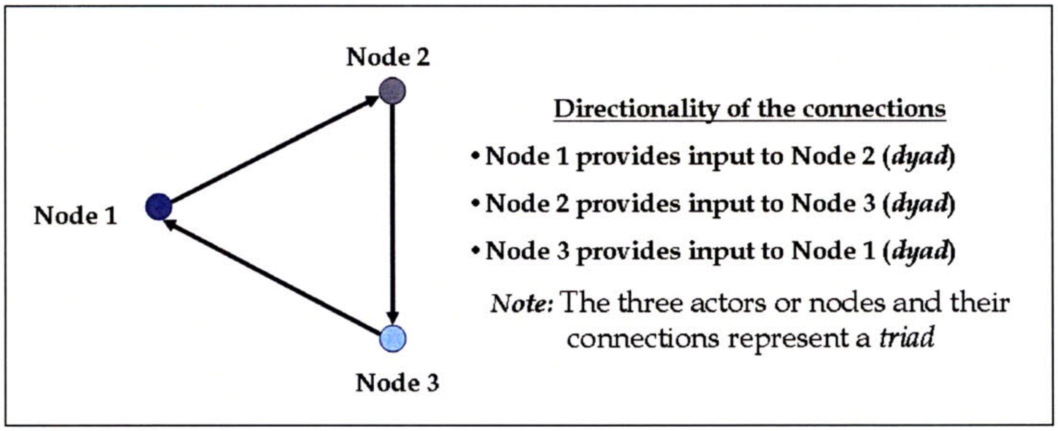

Figure 16. Basic elements of a sociogram

3.4.2. *Representations of Social Networks*

Social networks can be represented by matrices and / or graphs, as described next:

1) In the matrix format (also called *sociomatrix*), actors of the network are placed in the rows and columns and each cell typically has a binary digit, *1* or *0*, indicating the existence or absence of the interaction between its members, respectively.[6] [37] Based on matrix conventions, the actors in the rows are the information providers and those in the columns are the receivers; in other words, the directional tie from actor *i* to actor *j* is placed on the *(i,j)* cell of the matrix.

   It is worth highlighting that depending on the type of relation that is intended to be represented in a sociomatrix, various can be generated for instance, one reflecting the flow of information, another one the flow of money, etc.[54] The networks studied in the following sections are limited to flow of information and their matrices will always be diagonal. An example of a sociomatrix of *4* actors is shown in *Table 2*:

Actors	A	B	C	D
A		0	0	1
B	1		0	0
C	0	1		1
D	0	0	1	

Table 2. Example of a sociomatrix

   In the table above, it can be seen, for instance, that *A* doesn't provide any information to *B*, but *B* does give inputs to *A*.

   There are several software programs used to handle and analyze sociomatrices such as *UCINET* [49] and spreadsheet-type applications.

2) The graphical method for representing social networks uses *sociograms* in which actors are represented by nodes or points and their relationships to one another

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[6] Other numbers may also be used to provide more information about the interaction among actors, e.g., type of communication: *2* for face-to-face, *1* telephone conversations, *0* for no interaction at all.

are represented by lines [37]. More than the position of the nodes in the sociogram, it is the pattern of connections that is relevant. Just like in the sociomatrices, sociograms can show directionality between actors (*directed graphs)*, in which an arrow head is attached to each line indicating the direction of the relation (see *Figure 16*).

Software can be used to create sociograms such as *Netdraw* [34]; in fact, this uses sociomatrices to create the graphical representation of the network.

3.4.3. *Basic Measures of Social Networks*

From a social network, it is important to extract some measures regarding the prominence of the different actors in the network. A prominent actor is the one that is particularly visible to other actors in the network.[54] L.C. Freeman, 1979 [19] defined the following measures, among others, to understand the behavior of actors in the network: 1) *degree centrality,* 2) *relative degree centrality,* 3) *closeness,* 4) *relative closeness,* 5) *betweenness,* and 5) *relative betweenness.*

1) <u>*Degree centrality (or local centrality):*</u> It is relevant because it provides information about the number of other actors to which a point is adjacent.[37] A node with a high degree of centrality is considered to be central, i.e. "well-connected" in the network. With directed sociograms, it can be distinguished between the in-degree (or in-centrality for the relations that provide inputs to the actor) or out-degree (or out-centrality for the relations in which the actor provides information). Degree centrality can be expressed as:

$$C_D(n_i) = d(n_i) = \sum_j x_{ij} \qquad \textbf{Equation 2}$$

where n_i is the actor under analysis and x_{ij} represents the number of direct connections of a specific actor, either providing outputs (*ij*) or receiving inputs (*ji*) (see *Figure 17*).

2) *Relative degree centrality:* This measure allows comparison of two networks of different sizes (e.g., a central point with a degree of 10 in a network of 100 actors, wouldn't be as central as one with the same degree in a network of 20 nodes). This measure is equal to the number of connections of the actor divided by the possible amount of connections it could have in the network, [37] i.e.:

$$C'_D(n_i) = \frac{d(n_i)}{g-1}$$ **Equation 3**

where g is the total of actors in the network (group size) (refer to *Figure 17*).

3) *Closeness,* also called "global centrality" [37] expresses the distances among the various actors, i.e., how close an actor is to other nodes in the network. While the local centrality measures the amount of adjacent actors to a node, the global centrality measures the geodesic distance (shortest distance) between and actor and all its direct and indirect ties (the latter implies the distance between actors that are not adjacent). In a directed graph, paths are measured through lines that are in the same direction and just like in degree centrality, the terms "in-closeness" and "out-closeness" depending on the direction of the tie can be used. Closeness can be expressed as the reciprocal of the sum distance between a node and the rest of the actors given the fact that a node is "close" to a larger amount of nodes if it shows a low sum distance. Closeness can be calculated as:

$$C_C(n_i) = \left[\sum_{j=1}^{g} d(n_i, n_j)\right]^{-1}$$ **Equation 4**

where $i \neq j$ and $d(n_i,n_j)$ is the number of ties linking actors i and j considering the geodesic distance. The above equation calculates the inverse of the total distance that actor i is from the rest of the actors to which it is directly or indirectly connected (refer to *Figure 17*).[54] It is worth mentioning that $\sum_{j=1}^{g} d(n_i, n_j)$ is also known as *farness;* therefore, closeness in a network is basically the inverse of farness.

4) Relative closeness: similar to the relative degree centrality, a relative closeness can be estimated by incorporating the amount of possible connections an actor can have (see *Figure 17*): [54]

$$C_C'(n_i) = \frac{g-1}{\left[\sum_{j=1}^{g} d(n_i, n_j)\right]} = (g-1) \cdot C_C(n_i) \qquad \textbf{Equation 5}$$

5) Betweenness measures the extent to which an actor lies between several other nodes in the network.[37] Actors that connect two nodes can play the role of "brokers" or "gatekeepers" with the information. This condition where two points are connected at a distance of two ties through a third element has been called *structural hole* by Burt, 2001, and this is a situation where actors *"broker connections between otherwise disconnected segments."* [8] In this sense, actors with the highest betweenness could be considered the main *linchpins* of the network.

The following steps provide a way to calculate the betweenness of a particular actor *i*:

a) The total number of geodesics connecting two points *j* and *k* is calculated and it is assumed that all of them have the same probability $1/g_{jk}$ to be used for the flow of information between both actors.

b) In some geodesics, an actor *i* may appear at some point in the path. The number of geodesics containing *i* is then defined as $g_{jk}(n_i)$.

c) Given the definitions above, the probability of having i involved in the communication between j and k is equal to $g_{jk}(n_i)/g_{jk}$. The betweenness of i is the sum of all these probabilities over all pairs of actors in the network, disregarding i. The following equation provides the mathematical expression for betweenness:

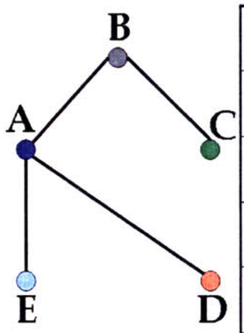
$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \qquad \textbf{Equation 6}$$

where $i \neq j$ and $i \neq k$ (see *Figure 17*).[54]

6) <u>*Relative Betweenness:*</u> as with previous measures, it is calculated by dividing C_B by the total number of pairs of actors disregarding n_i (refer to *Figure 17*): [19]

$$C_B'(n_i) = \frac{C_B(n_i)}{\frac{(g-1)(g-2)}{2}} \qquad \textbf{Equation 7}$$

Figure 17 below exemplifies the six measures for a given social network of *5* actors:



Node	CD	CD′	Cc	Cc′	CB	CB′
A	3	0.75	0.2	0.8	5	0.83
B	2	0.5	0.167	0.67	3	0.5
C	1	0.25	0.11	0.44	0	0
D	1	0.25	0.125	0.5	0	0
E	1	0.25	0.125	0.5	0	0

<u>Notes:</u>

-Total of actors in the network: $g = 5$

g-1=4 $(g-1)(g-2)/2=6$

-*CB* of A=5: (E↔ B), (E↔C), (E↔D), (D↔B), (D↔C)

Figure 17. Basic measures of social networks (modified from Freeman, 1979 [19])

The measures introduced in this section can be calculated using various computer applications oriented to analyze social networks such as *UCINET* or *Graph Definition and Analysis Package (GRADAP)*.[23]

3.4.4. *Additional Proposed Measures of Social Networks*

Considering that the analysis of social networks to be presented in the following sections will involve comparisons in the behavior of engineering teams (and not only independent variables), three additional measures are proposed which are derivations of those introduced in the previous section:

1) *Degree centrality of a set of actors:* It is equal to the sum of the degree centralities of the actors belonging to a particular group:

   $$C_{D\text{-}GROUP}(n_i) = \sum_m \sum_j x_{ij}$$ **Equation 8**

   where m represents the number of elements of a particular group. Dividing this measure by g-1 would provide the relative degree centrality for a group.

2) *Closeness of a set of actors:* Similar to the degree centrality for a set of actors, this is proposed to be the sum of the closeness of the actors within a group:

   $$C_{C\text{-}GROUP}(n_i) = \sum_m \left[\sum_{j=1}^{g} d(n_i, n_j) \right]^{-1}$$ **Equation 9**

   where $i \neq j$ and m is the number of actors of the group. The index could be multiplied by g-1 to get a relative measure.

3) *Betweenness of a set of actors:* As for the previous measures, it is basically the sum of the independent betweenness of the actors of the team:

$$C_{B\text{-}GROUP}(n_i) = \sum_{m} \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \quad \textbf{Equation 10}$$

where *i≠j* and *i≠k,* and *m* is the number of actors of the engineering team. The index could be divided by *(g-1)(g-2)/2* to get a relative measure.

3.5. Novel Methodological Approach: Comparison of the Technical and Social Dimensions of an Engineering System

The first step to be able to contrast any two conditions is to put them under the same comparative basis. In this case, a set of technical systems is to be compared and contrasted with a PD organization; to achieve this, two main tasks are proposed: first, identify the interactions among the technical systems and, second, identify the interactions among the members of the PD team. For the former, the next steps should be followed:

a) Each of the different variables of the engineering systems should be decomposed according to the MDO method and can be considered as *actors* of a social network.

b) Having developed a mathematical expression for each variable (whether a constant or a function) and identified the way variables feed each other, *directional ties* can be developed. For instance, if variable *A* is an input of *B*, then the information flows from *A* to *B*.

c) Having two of the basic elements of a social network (the actors and the ties among them), an *interaction diagram* showing how the elements of the systems interact can be developed. This would represent the interdependencies or *theoretical interactions* that should occur among the systems to multi-optimize the product. Therefore, this could be referred to as the *Theoretical Sociogram* (this would be equivalent to the *design interface matrix* [38]).

d) From the theoretical sociogram, theoretical social measures can also be estimated.

The second phase consists of developing the sociograms of the organization. It is important to mention that the intended comparison is between the systems and the engineers working on them; therefore, the organizational study should be focused on these PD members. The proposed methodology is outlined below:

a) To get their interactions, a questionnaire should be developed and applied to them, asking for information about their ties with other members of the team.

b) One of the concerns in a PDP is the timing at which cross-functional interfacing occurs as this may have an influence on the cost, quality and overall timing of a project. Therefore, the questionnaire should ask for information pertaining to different phases of the project.

c) Once the questionnaires have been completed, different sociograms can be constructed (one per PD phase). These diagrams represent the *Actual Sociograms* of the project (this would be equivalent to the *team interaction matrix* [38]).

d) The respective social measures should also be obtained from these two networks.

With the two areas of the analysis, both the technical and the organizational, under the same communication platform (i.e., a network structure), it would be possible to compare them by analyzing the ties between the actors as well as the respective network measures. Differences then should be understood through interviews with actors of the PD team.

4. EMPIRICAL ANALYSIS APPLYING TECHNICAL AND SOCIAL MAPPING TOOLS TO PD PROJECTS

The purpose of this chapter is to show how the methods introduced in the previous chapter can be applied to analyze engineering systems both, the technical and organizational dimensions. First, a description about the elements that were taken into account for selecting the project is provided. Afterwards, the decomposition of the technical systems is presented, followed by a description of how the social capital was evaluated.

4.1. Considerations for Project Selection

Obviously, easy access to information is vital to the choice of a project. In this particular instance, it must be twofold: First, technical information about the product architecture should be available; second, there should be access to the individuals working in the project for surveys and interviews. This can also be enabled if a recent past project or a project in its last development phases is studied (with the time, documentation becomes hard to track and engineers are typically appointed to other roles and/or responsibilities). Besides, engineers can provide a fresh perspective about the things that went wrong and how they can be improved.

It is relevant to mention that advances in long distance collaboration tools now allow the distribution of the PDP in offshore sites as well as to global partners. This growing trend has led to many projects now being undertaken by different engineering sites located around the world (a.k.a. Global Product Development or GPD).[48] Therefore, the selected project has to have this feature (this will prove particularly relevant during the study of social networks in subsequent chapters).

In order to perform the analysis of the engineering systems, the following items were also taken into account:

1) An actual road vehicle project under design by an automotive OEM was selected.

2) Some of the product's systems were decomposed based on the MSDO methodology, i.e., definition of *Boundaries, Objectives, Design Variables, Constraints, Parameters* and *Submodules*. While a typical car is made up of a considerable number of systems, it was deemed that selecting a few of them would provide proper information to compare and contrast the interaction of actual vehicle systems and engineering teams. Given that the present study is intended to analyze the enablers and obstacles of these interactions in a PD organization, the selected modules should show a considerable amount of technical connections as well as adequate diversity in the product's functions (the proposed submodules are Aerodynamics, Weight, Tires, Transmission, Vehicle Performance, Gradability, Braking, Steering, Handling and Ride and will be further described in the *Submodules* section).

3) Each of the different terms within the submodules was characterized by an analytical transfer function based on physics models developed by J. Y. Wong, 2001 [57], Jack Erjavec, 2000 [17] and Bosch's Automotive Handbook, 2004 [6]. As previously described in *Chapter 2*, in practice, these transfer functions are typically represented by numerical methods through computer simulations and validated in numerous occasions with physical testing. However, the mathematical models were considered to provide an adequate level of information for understanding the main interactions occurring among the selected vehicle systems.

4.2. Project Description

The project used for the analysis was a vehicle under development by a global automotive manufacturer. The main engineering sites contributing to the development of this particular product were located in Japan, Europe and North America (NA). In fact, from a final product perspective, each site was responsible for integrating its own final product variant for its regional market; this means putting together the appropriate systems and components to arrive at a final product (the Japanese site integrated the product for Japan, for instance). However, at a component and system level, each site could own the responsibility for multiple regions (e.g., the floor panel was developed by a single site for all the markets). For this particular study, the North American version was considered.[7]

The vehicle consisted of a 4-door sedan with front-wheel drive (FWD) manual transmission to be sold in NA. Aside from some minor styling modifications, the North American version had to meet different federal and market requirements with respect to its European and Japanese counterparts, driving differences in Noise and Vibration Harshness (NVH)[8] performance, cooling systems modifications, powertrain calibration changes and different safety-related content, to name a few. It is worth highlighting that while the NA variant doesn't represent the creation of a brand new vehicle but a customization of an existing one, it is judged that several of the findings of the present study will not be limited to this type of projects; it is deemed that they could be extrapolated to a variety of GPD projects.

It is important to mention that in order to maintain product confidentiality, some of the terms in the analysis were modified or normalized; however, this shouldn't impact the methodology outlined in the present study. Also, some pictures of road vehicles are shown to better explain some of the terms of analysis; however, they do not represent the vehicle described above and can be deemed to be generic.

4.3. Definition of Boundaries

Following a typical MSDO process, the analysis started by defining the boundaries of the system to be analyzed. Since the ultimate purpose of the study was to understand

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[7] As explained before, this version was made up of components and systems developed in any of the three different sites, but integrated in the North American engineering center for its own market.

[8] According to the manufacturer, NVH is the product integration area that attempts to address undesired noise and vibrations experienced by the occupants inside a vehicle.

the interactions of PD teams in the presence of competing objectives, it was considered that the selected boundaries should include systems meeting the following requirements:

1. They had to show functional connections with each other based on their mathematical description (e.g., outputs from one system should become inputs of another system). When performing the comparison between the theoretical system and the organizational behaviors, this requirement was intended to allow an understanding of how Product Development engineers in a particular organization interact given highly connected systems.

2. They needed to be handled by different engineering teams in a Product Development organization. The purpose of this was to understand how engineers belonging to different teams interact with each other (a.k.a. cross-functional interactions).

3. They must show competing objectives in order to understand the level of interactions that engineering teams should and actually have when trade-offs have to be made.

To identify the systems that met the above criteria, it was decided to start by identifying some vehicle attributes[9] that were influenced by some systems and/or components in common in the project described above. Four vehicle attributes were identified (refer to the next sections to review the decomposition of the system):

1) Aerodynamics (drag, wind noise)
2) Vehicle Dynamics (in particular, ride and handling)
3) Performance (acceleration, fuel consumption)
4) Weight

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[9] The manufacturer defines Vehicle Attributes as the elements that characterize the vehicle's functions and which are perceived by the customer (i.e., vehicle level requirements). These Vehicle Attributes are handled by different Attribute Engineering Teams.

Aerodynamics is a branch of dynamics that studies the influence of air on a moving object (this includes the resultant forces and how motion of the object is affected by the air). In particular for a ground vehicle, the aerodynamic resistance or drag Ra (which is the force that opposes a car's motion when it passes through air) becomes critical due to the growing emphasis on fuel economy, emissions and vehicle performance, among other factors [17]. The *Ride characteristics* of a ground vehicle refer to its vibration due to irregularities in the road, while the *handling qualities* are related to the response of the car to the inputs of the driver as well as its capacity to stabilize after external disturbances [57]. The *Performance* of a vehicle refers to its potential to accelerate as well as decelerate, pull a load and negotiate grades typically in a straight line [57]. Finally, the weight of a car refers to its total mass multiplied by the acceleration of the Earth's gravity (defined as $g=9.81$ **m/sec**^{2} as defined in the *Parameters* section).

Keeping these attributes in mind, it is now possible to identify the objectives that are to be optimized in the analysis.

4.4. Definition of Objectives

The main objectives were identified based on the targets of the product under study. For the present analysis, the terms *objective* and *target* are used for different purposes and it is relevant to highlight the difference: *objective* is used to refer to the function that serves as the criterion to define an optimal design [36]; on the other hand, a *target*, as referred to within the manufacturer's engineering team, is the behavior desired from the product, which must be verifiable by inspection, analysis, demonstration, or testing. In other words, the target is the instantiation of a product requirement which a design team aspires to meet.

Based on the distinction above, targets are typically set-up at the beginning of the project; however, due to the interactions of the vehicle's systems, limitations on the number of new parts,[10] cost restrictions, development of new technologies, conflicting behaviors and/or changes in the project's assumptions, the intended targets may be under- or overachieved.[11] Consequently, by using the objectives it can be determined by how much the vehicle under- or over-performs in each particular area, providing, as a result, a basis for characterizing the "best" design [36].

Following the MSDO methodology, the targets are included in the ***Parameters Vector*** and the *Objectives* are placed separately in their own vector. The objectives considered for the present study are:

- Speed
- Performance
- Grade
- Braking Distance
- Directional Stability
- Ride Ratio
- Drawbar load

It can be noticed from the list above that Fuel Economy was not explicitly included as an objective. This is because a great deal of the fuel economy-related work had previously been performed by the European site, and as long as the ranges of the design variables are maintained, there shouldn't be an unexpected degradation (e.g., weight, front area, etc.).

Also, to simplify the calculation during the optimization process, a global objective was defined based on the squared error of the targets and the actual calculated value. Each squared error was multiplied by a weight factor based on the priorities of the product.[56] At the end, the idea was to minimize the global objective to make it as close as possible to zero (i.e., should the difference between the target and the actual

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[10] In today's automotive industry, many manufacturers base their new designs in previous designs; therefore, they keep a certain amount of carry-over components as a way to reduce costs and time.

[11] Typically, a target can only be underachieved if it doesn't represent a regulatory non-compliance or if the cost-benefit ratio of achieving the target is deemed extremely high.

calculated values be equal to zero, all targets would have been achieved). For further information about the calculation of the global objective, refer to the *Appendix* section *9.1*.

Table 3 summarizes the information of each partial objective; the last column, *Inputs,* refers to the ID number of the variables required to calculate the objective. For the detailed description of the analytical transfer function behind each objective, refer to the *Appendix* section *9.1*.

	Symbol	ID #	Name	Value	Units	Target	Eng. Team	Inputs
Objectives	SF	1	Speed Factor (fwd - manual)	6.62	d.l.	Maximize (>0)	Energy	**22,9**
	PF	2	Performance Factor (fwd - manual)	-2.92	d.l.	Maximize (>0)	Energy	**16,3**
	GF	3	Grade Factor (fwd - manual)	-0.23	d.l.	Maximize (>0)	Energy	**29,1**
	BD	4	Braking Distance Factor	6.24	d.l.	Minimize (<0)	Brakes	**4,8**
	DS	5	Directional Stability Factor	0.00	m	Maximize (>0)	Vehicle Dynamics	**28,4**
	RF	6	Ride Ratio Factor	0.2	d.l.	Minimize (<0)	NVH	**27,10**
	DLF	7	Drawbar Load Factor	0.0	d.l.	Maximize (>0)	Energy	**14,20**

Table 3. Summary of system objectives

It is important to mention that the column *Value* in *Table 3* and in the subsequent tables refers to the final value after conducting a linear programming optimization minimizing the global objective. Based on this, the global objective was equal to *3.9*.

4.5. Definition of Design Variables

The *Design Variables* were those items that according to the project's assumptions could be modified to achieve the intended performance for the NA version. *Figure 18* summarizes some of the variables. For a more detailed description of each variable, refer to section *9.2* of the *Appendix*.

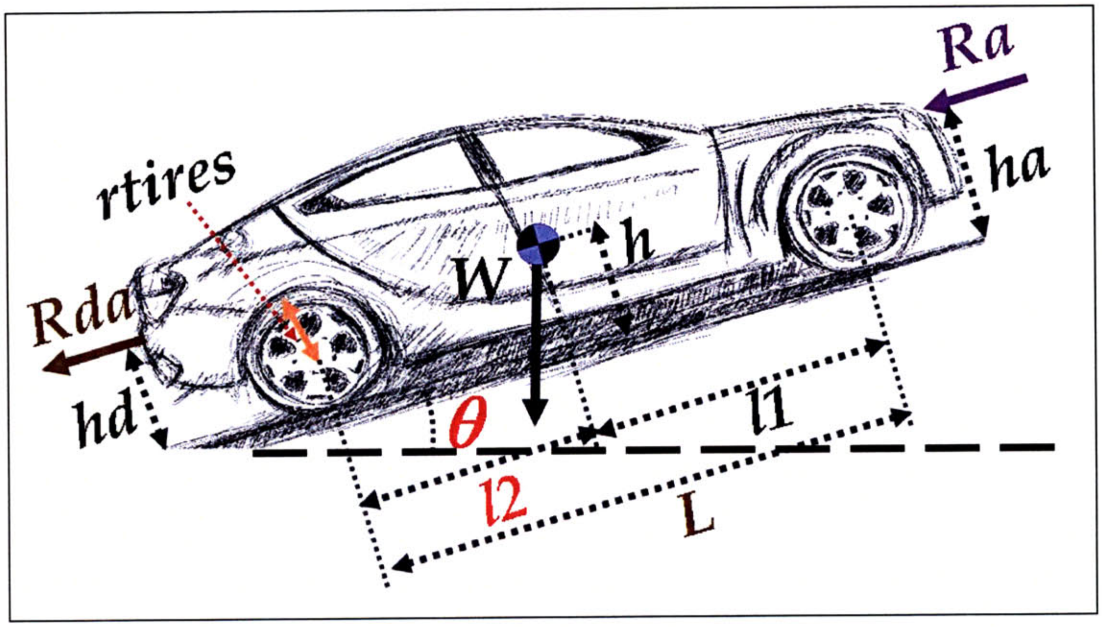

Figure 18. Selected forces and vehicle's dimensional variables

Also, the next table sums up all the design variables and it also shows the Engineering Team responsible for each term:

	Symbol	ID #	Name	Value	Units	Target	Eng. Team
Design Variables	Ha	1	Application of the aerodynamic resistance	0.920	m	0.92-0.97	Aerodynamics
	Hd	2	Drawbar hitch location	0.551	m	0.551-0.590	Energy
	H	3	Center of gravity (z-direction)	0.910	m	0.910-1.020	Weight
	l1	4	Center of gravity w.r.t. front axle	1.3	m	0.95-1.50	Weight
	W	5	Vehicle's weight	11,600.00	N	11,600-13,300	Weight
	Af	6	Front end characteristic area	2	m^2	1.8-2.0	Studio
	Cd	7	Vehicle's drag coefficient	0.43	d.l.	0.42-0.44	Aerodynamics
	Rtires	8	Rolling radius of the tires	0.35	m	0.35-0.36	Wheels / Tires
	Eax	9	Gear ratio in the drive axle	3.8	d.l.	3.6-3.8	Powertrain
	Caf	10	Cornering stiffness of the front tires	15,185	N/rad	14,000-32,400	Wheels / Tires
	Car	11	Cornering stiffness of the rear tires	28,650	N/rad	14,000-32,400	Wheels / Tires
	kf	12	Spring stiffness of the front suspension	60,000	N/m	60,000-75,000	Chassis
	kr	13	Spring stiffness of the rear suspension	60,000	N/m	60,000-75,000	Chassis
	Rda	14	Actual Drawbar load	1,000	N	0-1,000	Energy

Table 4. Summary of design variables

4.6. Definition of Parameters

After a review of the project assumptions and conversation with some engineers, the *Parameters* vector was constructed based on the following criteria:

a. Physical dimensions of the car were selected that were to be carried-over from a previous product based on the project assumptions and that therefore could not be changed.

b. Specifications of some components and/or systems that, as before, were considered to be carry-over from a previous product.

c. Physical constants or parameters external to the vehicle.

d. Test conditions and/or specifications as defined by the manufacturer's internal procedures or federal regulations.

e. As described in the *Definition of Objectives*, the initial targets of the product were also considered as parameters.

A summary of all the parameters appears in the next table. Further description of each of the parameters is provided in the Appendix in section *9.3*:

	Symbol	**ID #**	**Name**	**Nom. Value**	**Units**	**Eng. Team**
Parameters	nu	1	Road Adhesion Coefficient	0.8	d.l.	Vehicle Dynamics
	Grade_test	2	Test gradability	2.0%	%	Energy
	L	3	Vehicle's Wheelbase	2.46	m	Architecture
	Sb	4	Desired braking distance	32	m	Brakes
	Es	5	Steering gear ratio	25	d.l.	Steering
	Radius	6	Turning Radius of the vehicle	20	m	Steering
	ry	7	Vehicle's radius of gyration	1.33	m	Architecture
	Vair	8	Speed of the wind	-2	m/sec	Aerodynamics
	Ro	9	Mass density of the air	1.2	kg/m^3	Aerodynamics

	Me	10	Engine Torque	150	N-m	Powertrain
	Memax	11	Maximum engine torque	160	N-m	Powertrain
	ne	12	Engine Speed @ maximum vehicle speed	600.00	rad/sec	Energy
	ne1	13	Engine speed @ maximum engine power	544.54	rad/sec	Energy
	nt	14	Transmission Efficiency	94%	%	Powertrain
	i	15	Longitudinal Tire Slip	4.5%	%	Wheels / Tires
	a	16	Desired vehicle acceleration	3.5	m/sec^2	Energy
	td	17	Response time of the brake system	0.005	sec	Brakes
	tr	18	Braking reaction time of driver	0.05	sec	Brakes
	g	19	Earth's gravity	9.81	m/sec^2	Weight
	Rd	20	Maximum Desired Drawbar load	1,000	N	Energy
	is	21	Slip of the vehicle running gear	3.0%	%	Powertrain
	Vmax	22	Desired maximum vehicle speed	55.56	m/sec	Energy
	Kg	23	Gear ratio factor	0.7	d.l.	Powertrain
	V	24	Vehicle speed	23.61	m/sec	Energy
	Vb	25	Vehicle initial speed prior a braking event	22.22	m/sec	Brakes
	Vs	26	Vehicle speed for evaluation of steering performance	26.39	m/sec	Vehicle Dynamics
	des_ride_ratio	27	Desired ratio of radius of gyration to oscillation centers for ride	1.00	d.l.	NVH
	des_direc_stab	28	Desired directional stability	0.10	m	Vehicle Dynamics
	Grade	29	Desired gradability	30%	%	Energy

Table 5. Summary of parameters

4.7. Definition of Submodules

In the definition of the submodules, the level of analysis that is going to be conducted must be defined. From high-level representations of major subsystems to individual components that make these subsystems can be utilized. However, the level of specificity should be driven by the research question and be meaningful given the context.[27] Therefore, it was considered that it was more insightful to define them at a system or attribute level than at a raw component level (e.g., nuts and bolts). Based on this, the following ten submodules were defined:

- Aerodynamics
- Weight
- Tires
- Transmission
- Performance
- Gradability
- Braking
- Steering Performance
- Handling
- Ride

The submodules were organized not only based on the engineering teams responsible for estimating or measuring them, but also on the physical and mathematical interrelationship between the variables (i.e., variables closely related were placed in a similar module). The latter was determined by the similarity of engineering tools used to analyze them, either virtual or physical. For instance, *Table 11* in section *9.4* shows a summary of the variables of the *Aerodynamics* submodule. While *Rab* and *Vrb* are within this module, they are actually used by the *Brakes* team. However, the *Aerodynamics* team is actually responsible for estimating them and uses the same tools (e.g., Fluent and wind tunnel tests) as those required to calculate *Ra* and *Vr*.

A detailed description of the variables within each module is provided in section *9.4* of the Appendix. While the analysis doesn't show all the elements that need to be considered for designing the selected systems of a vehicle, those presented will allow for an understanding of the interactions between a system and also, among some of the members of an engineering organization. As mentioned before, herewith mathematical expressions are used to describe how each team deals with its different variables; nevertheless, in practice, computer models (e.g., CAE, CFD, CAM) and physical tests are typically used to perform these assessments. Before presenting the equations of each module, a brief description about the tools used by the manufacturer to perform more detailed analyses is also included.

4.8. Constraints

Based on the experience of some engineers, benchmark studies, components' limitations, safety factors, federal regulations and market needs the following constraints have been identified:

1. The drag force must be kept below *1,300 N* to be in a competitive range.

2. The load in the front axle can't be greater than *7,800 N* due to the mechanical properties of front suspension components.

3. The load in the rear axle can't exceed *8,240 N* because of the mechanical properties and safety factor of the rear axle.

4. The total stopping distance during a braking test can't be by any means greater than *40 m;* otherwise, the federal regulations of some countries wouldn't be met (e.g. Mexico). Therefore, as a safety factor, the automaker restricts the stopping distance to be lower than *38 m*.

The table below summarizes the constraints of the analysis:

	Symbol	Name	Nom. Value	Units	Eng. Team
Constraints	Drag Force	Drag Force	<1300	N	Aerodynamics
	Wf	Load in the front axle	<7,800	N	Weight
	Wr	Load in the rear axle	<8,240	N	Weight
	Stot	Total Stopping Distance	<38	m	Brakes

Table 6. Summary of the analysis constraints

4.9. Functional Analysis: N^2 Diagram

Functional analysis is *"the process of identifying, describing, and relating the functions a system must perform in order to fulfill its goals and objectives."* [33] This type of analysis allows determination of the requirements with which a set of systems must comply, it provides elements to evaluate their performance and establish trade-offs between the internal subsystems. One of the techniques used to perform functional analyses is called the *Design Structure Matrix* (DSM) which is a system analysis and project management tool that represents the interdependencies and information flow within and between different domains (e.g., systems, tasks, components) [43]. There are different types of DSMs depending on the application, and one of them is the *N^2 Diagram*, which shows the data or signal exchange between two or more systems. This diagram is basically a matrix that shows the cross-functional interactions of systems at a particular hierarchical level [33]. *NASA*'s handbook suggests the construction of the matrix as follows:

1. The main diagonal is made-up by the *main modules* or functions of the system. In the present study, it refers to the *Design Vector, Constraints, Parameters, Submodules and Objectives.*

2. Each column is filled with the inputs required by each function to perform its contribution to analysis of the system (see *Figure 19*).

3. Rows represent the outputs of each function (see *Figure 19*).

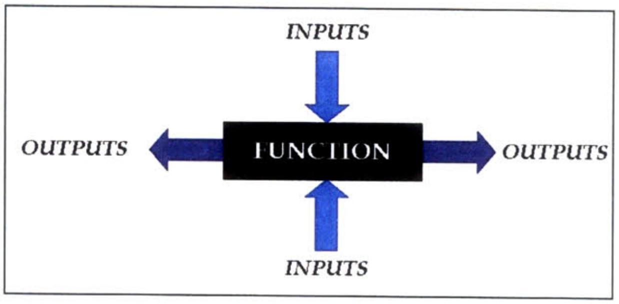

Figure 19. Interpretation of columns and rows in the N^2 diagram

4. Blank cells represent the lack of interaction between functions (refer to *Figure 20*).

5. The data shown in the matrix flows in a clockwise direction. In the *N^2 Matrix,* should only sequential information flow be present between a set of systems, in contrast to other DSMs, all interactions would appear above the main diagonal; elements below the diagonal represent a loop in the information flow and it means that a system under development is dependent on the outcomes of another to be designed later. In some cases, the latter can be resolved by changing the order in which the systems are designed (some algorithms for DSMs have been developed for this); however, if this is not the case, it means that the systems are coupled [51].

6. Using *Figure 20* as an reference, the position of a particular cell is important to understanding how the information flows in a *N^2 Diagram*: Functions to the left of the arrow represent the information providers and those to the right, the receivers (e.g., in *F1* → *F2* information flows from *F1* to *F2*).

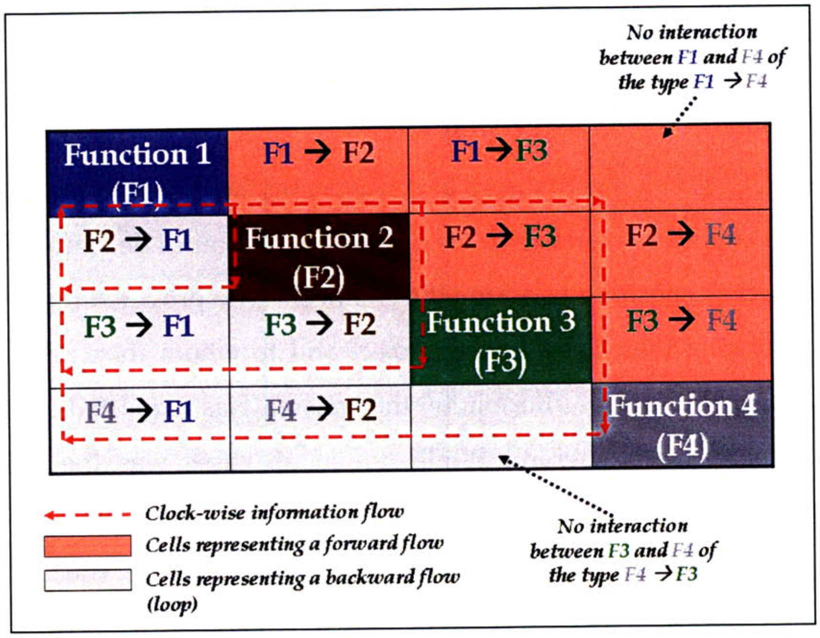

Figure 20. Construction of an N^2 diagram (modified from [33])

4.10. Sensitivity Analysis

In order to determine the strength of some of the ties between the constituents of the product, a sensitivity analysis is proposed. The idea is that high relative sensitivity among constituents would imply that a link is *strong*; on the other hand, low relative sensitivity would imply that the link among constituents is *weak*. This will become relevant when comparing the technical and organizational links: If a link occurring in the architecture of the product is not present in the organization (or is handled by an intermediary), i could be due to the low sensitivity among the variables. On the other hand, if the sensitivity is high, yet the interaction in the organization is not present, it could infer that a communication obstacle might be present.

It is proposed that absolute relative sensitivities[12] lower than or equal to *0.5*, would represent weak ties; on the other hand, those above *0.5* would represent strong ties. For further information about the calculation of the relative sensitivities, refer to the *Appendix* section *9.5*.

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[12] Absolute relative sensitivity is referred to as the absolute value of the relative sensitivity.

4.11. Organizational Elements of the PD Team

4.11.1. Questionnaire and Phases Definition

As described in *Chapter* 3, the first step in constructing the *Actual Sociogram* was to apply a survey to the engineers working in the systems or attributes decomposed in previous sections. The survey consisted of asking the engineers who provided them with the most input for completing their tasks in the project and to whom they provided the most information. Also, the type of information they shared was requested in order to match it with the theoretical sociogram. While not in all cases was the specific type of information they shared obtained from the surveys, follow-up interviews with some managers and engineers of the program allowed for clarification. The latter also helped to uncover mistakes that may have taken place when the respondents filled the survey.

Also, the questions referred to two different phases of the program, which, in order to maintain the confidentiality of the automaker, will be named as *Phase I* and *Phase II*. The two phases are divided by a milestone based on the PDP used by the company to develop automobiles, and the purpose of studying them was to understand whether there was a difference in the interactions among the network actors at these two stages of the vehicle program (in other words, the time factor is added to the study). Generally speaking, the two phases can be described as follows:

- *Phase I:* In this phase, the targets that the vehicle must meet are defined based on the customers' needs as well as current and expected trends of the market. At the beginning of this phase, several configurations and concepts are evaluated until it gets narrowed down to a couple of alternatives by the end of the phase. During this phase, great flexibility is encountered by engineers to change parts given the fact that most teams are evaluating different alternatives and nothing is frozen yet.

  Throughout this phase, the unavailability of physical parts and the high costs of prototypes lead to the engineering development being executed mainly with the use of virtual tools (CAE, CAD, CFD, etc.) and with a very low usage of physical prototypes. Also, since the design evolves with significant speed at this point, detailed information on the new product is hardly available; therefore, the virtual and physical models are built up based on surrogate designs coming from previous products.

Phase II: The phase begins by freezing a single design concept. At this point, more detailed data is generated including drawings, virtual models and even physical parts. Since more detailed data is developed and more physical models are available, CAE models are better correlated to actual tests and therefore are typically more accurate.

In this phase, radical changes to the vehicle architecture are not feasible anymore, for they could delay the project or increase the costs; consequently, most of the efforts are focused on meeting the program targets with the given assumptions. By the end of this phase, the entire design must be frozen and the final physical validation takes place. Once the validation is concluded, the engineering work is considered complete.[13]

4.11.2. Actual Network Statistics

The survey was applied to *21* engineers working at four different engineering sites: at Germany, Japan, Mexico and the USA (see *Figure 21*). Complementing the results of the surveys, interviews with six managers and engineers took place to complete the social network.

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[13] After the conclusion of Phase II, what could be called Phase III begins and it is mainly oriented toward the manufacturing of the product. The latter was not analyzed because by the time the present work was developed, the vehicle under analysis hadn't been transferred to the manufacturing site; besides, during this phase any changes in the design are kept to a minimum and are implemented mostly to correct concerns encountered during the assembly process.

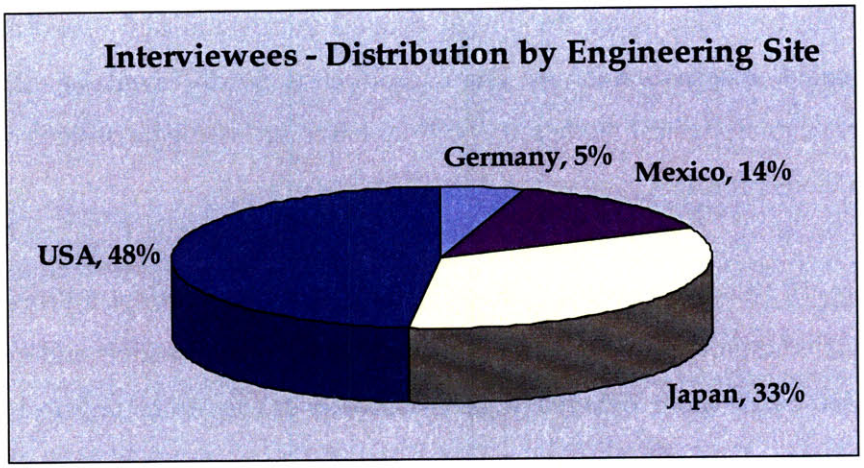

Figure 21. Distribution of interviewees by engineering site

The results of the surveys allowed the construction of a network of *223* actors belonging to about *38* engineering teams (see *Figure 22*) distributed in *11* engineering sites around the world (see *Figure 23*). It is important to mention that these *223* individuals do not represent all the people who were involved in the project, but just those who were referenced in the surveys.

A brief description of the responsibilities of each engineering group is provided in the *Appendix* at *section 9.8*. Interestingly in the above figure, the engineering group with the greatest amount of actors corresponds to *Program Management*. One reason for this could be that a global project demands significant efforts to coordinate the deliverables of all teams to make sure they occur on time and within a pre-established budget. However, this can only be confirmed by comparing a project of a similar magnitude developed in a single site and the present work doesn't provide enough data in this regards.

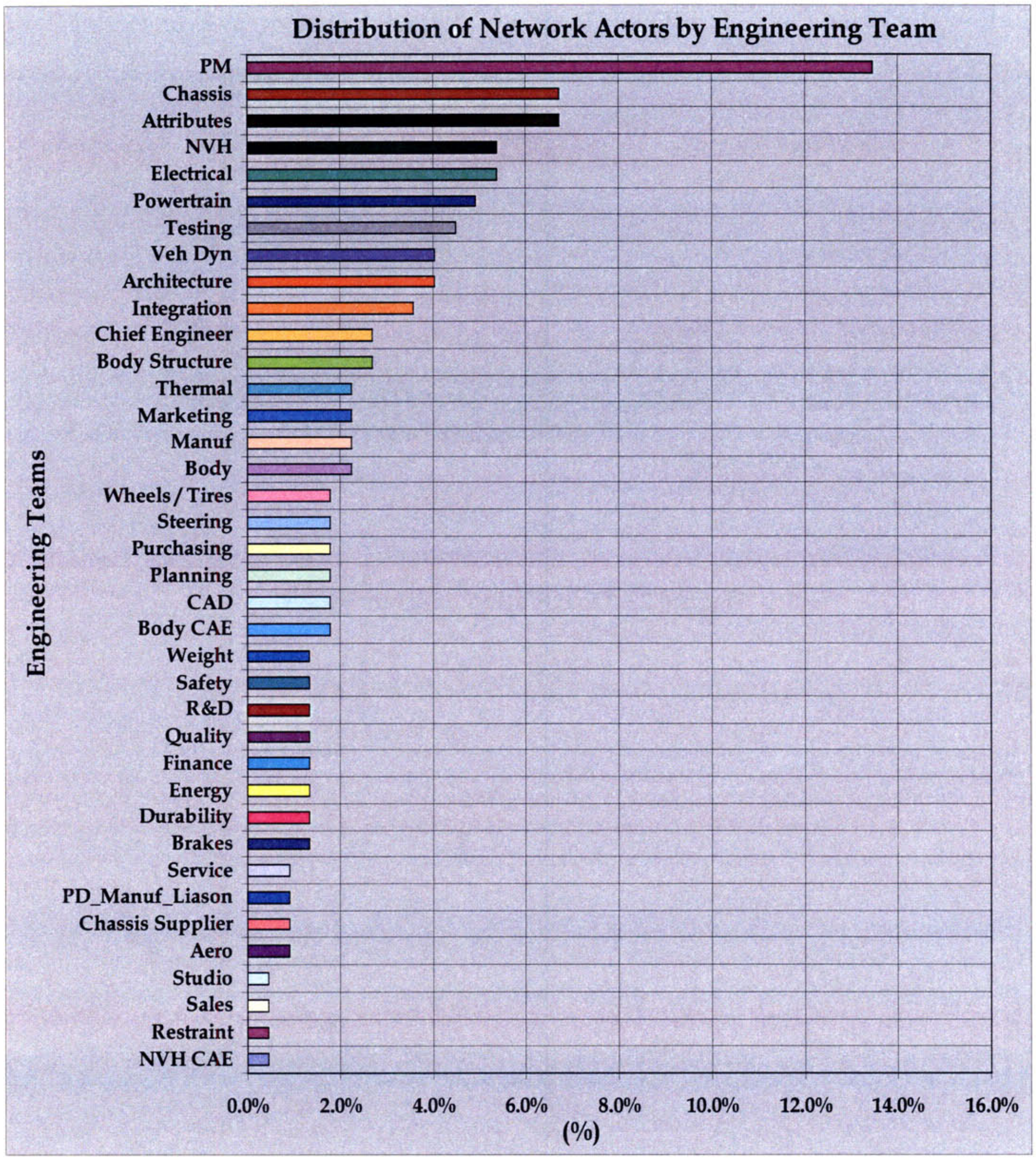

Figure 22. Distribution of network actors by engineering team

As mentioned during the description of the project, since it was to be delivered in North America, it is expected that most actors will be located in the USA, where the OEM has its main engineering center in NA. However, given that a significant part of the components and systems are shared by Europe and Japan, these sites also show a great participation in terms of total actors (see *Figure 23*).

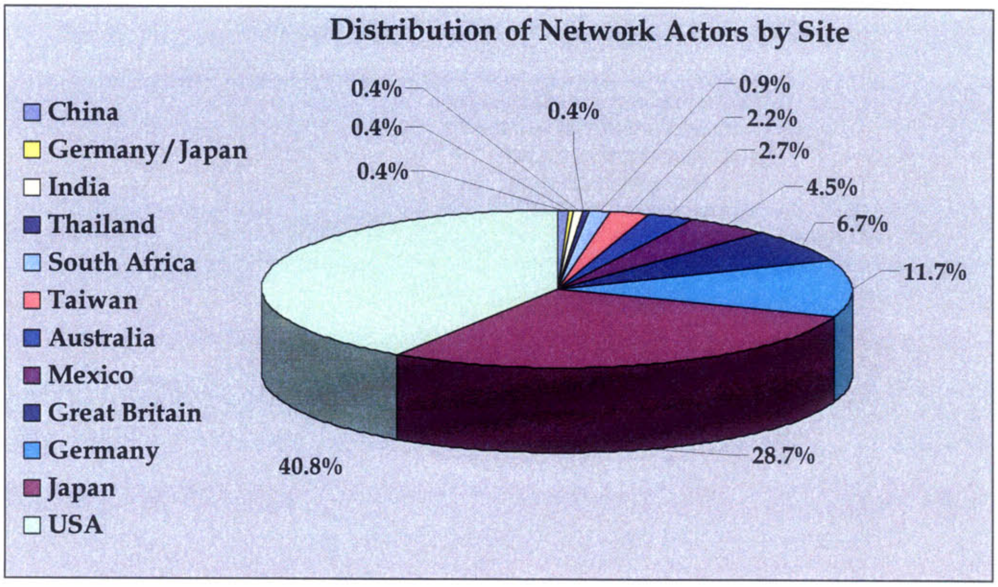

Figure 23. Distribution of actors by site

5. RESULTS OF THE ENGINEERING SYSTEM ANALYSIS

This chapter is intended to provide the results when the methods for the analysis of engineering systems were applied to an actual PD team. It begins by presenting the resulting *N^2* Diagram of the system decomposed in *Chapter 4*. With this and the overall decomposition of the system, the theoretical sociogram is constructed. Subsequently, the results of the surveys applied to the PD team are used to construct the organizational network and the actual sociograms are presented.

The final part of the chapter compares and contrasts the actual interactions among the engineers working in the product with the internal interactions of the systems (i.e., actual vs. theoretical sociograms). With this, the intention is to highlight the differences in both interactions so that after some interviews with the PD team, it will be possible to understand the causes behind them.

5.1. The Resultant N^2 Diagram

Using the main modules of the attributes/systems described and IDs assigned to each variable, the corresponding N^2 diagram can be constructed as shown in *Table 7**Error! Reference source not found.***. The diagram clearly outlines the elements of the system that lead to the cross-functional interactions of the systems / attributes. I could be said that this diagram provides a view of the architecture of the product.

Initially, there were some loops in the matrix; however, after several arrangements in the location of the modules in the *N^2 diagram*, the variables were set up in such a way that most of them were avoided. Still, the acceleration of the vehicle would lead to a loop for it is needed to estimate the reactions at the front and rear axles by the *Weight* module and it is actually calculated by the *Performance* module. To address this, an initial acceleration (a.k.a. desired vehicle's acceleration in the *Parameters* vector) is assumed for the *Weight* module and the loop, at least in the matrix, is eliminated. With these simplification, the matrix infers a sequential design process among the selected submodules, starting from the aerodynamics of the vehicle and ending in its ride. However, in reality this is not the case: Having a sequential process such as the one depicted would require a long time to get completed. Consequently and due to the lead time it takes for the engineers responsible for each of the modules to complete their design, they have to work in parallel. This means that in the initial phases of the project, they have to assume the inputs coming from other teams (such as the vehicle's acceleration). These assumptions are then refined as the design progresses and therefore, demands continued interaction among the teams connected by variables.

It is also worth mentioning that conflicting objectives may lead to trade-offs. This may translate to the change of objectives and may force several submodules to revisit their assumptions and rework a few areas of the design. In this sense, the diagram should permit engineering teams to visualize what decisions affect other teams and accelerate this process.

N-SQUARE DIAGRAM OF SELECTED VEHICLE SYSTEMS / ATTRIBUTES

Design Vector	Constraints	Param. Vector	Submodules										Objectives
Design Vector			6,7	1,2,3,4,5,14	5	5,8,9	5,14	5	3,4,5,6,7	10,11		4,9,12,13	14
	Constraints												
		Param. Vector	8,9,24,25	2,3,16,19	1,24	10,11,12,13,14,15,21,22,23			1,2,3,9,17,18,19,25	3,5,6,19,26	3,19,26	7,19	3,4,16,19,20,22,26,27,28,29
			Aerodyn.	1			1		2				
				Weight	2,3		1		4	2,3		4	3
					Tires	5,6	1,4		6,7				
						Trans.	8,10						9
							Perfor.	2					
								Gradability					1
									Braking				8
										Steering Perfor.	1		1
											Handling		4
												Ride	10
													Objectives

Table 7. N² diagram of the decomposed vehicle attributes / systems

5.2. Construction of the Resultant Theoretical Sociogram

The *Theoretical Sociogram* was constructed using the information of the *N*² diagram and the links among the variables of the decomposed system (refer to the previous chapter). Using *Netdraw*, the sociogram was developed; the colors of each node represent the module they belong to in the *N*² diagram previously described (see *Figure 24*).

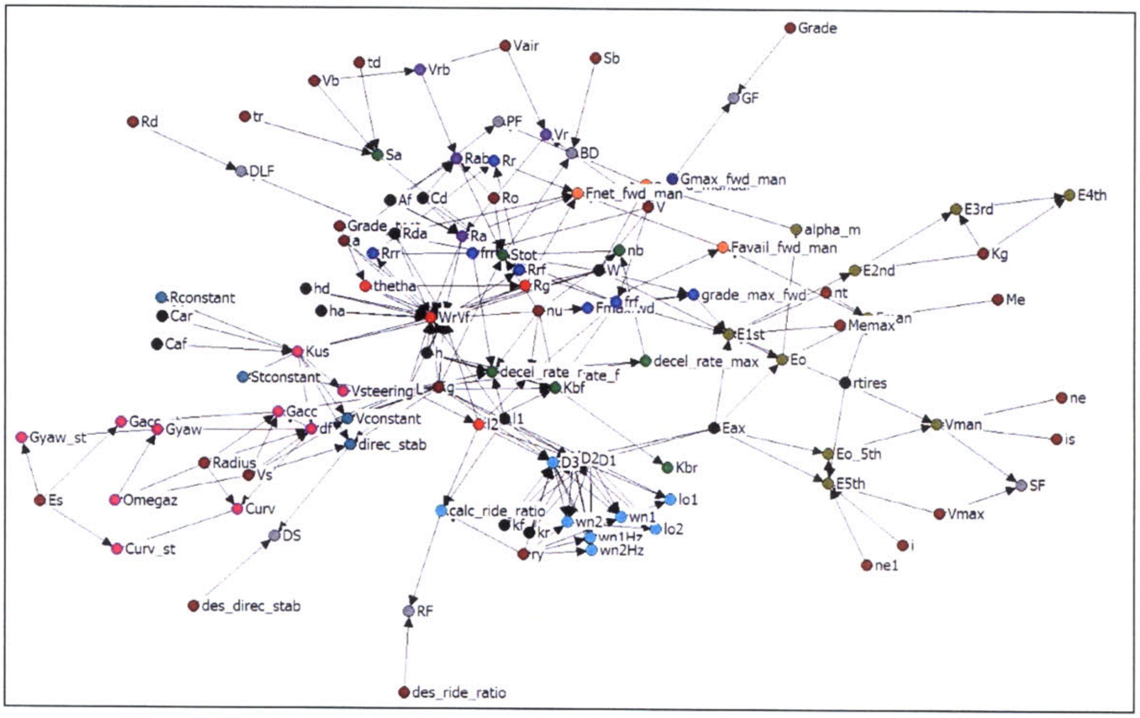

Figure 24. Theoretical sociogram of the decomposed systems (variable-based)

Each of the variables shown in the diagram above is linked to an engineering team in the organization under analysis. Using this information, it is possible to create an equivalent diagram but showing the interrelation of the engineering teams. This will permit an easier comparison with the actual sociograms (refer to *Figure 25*).

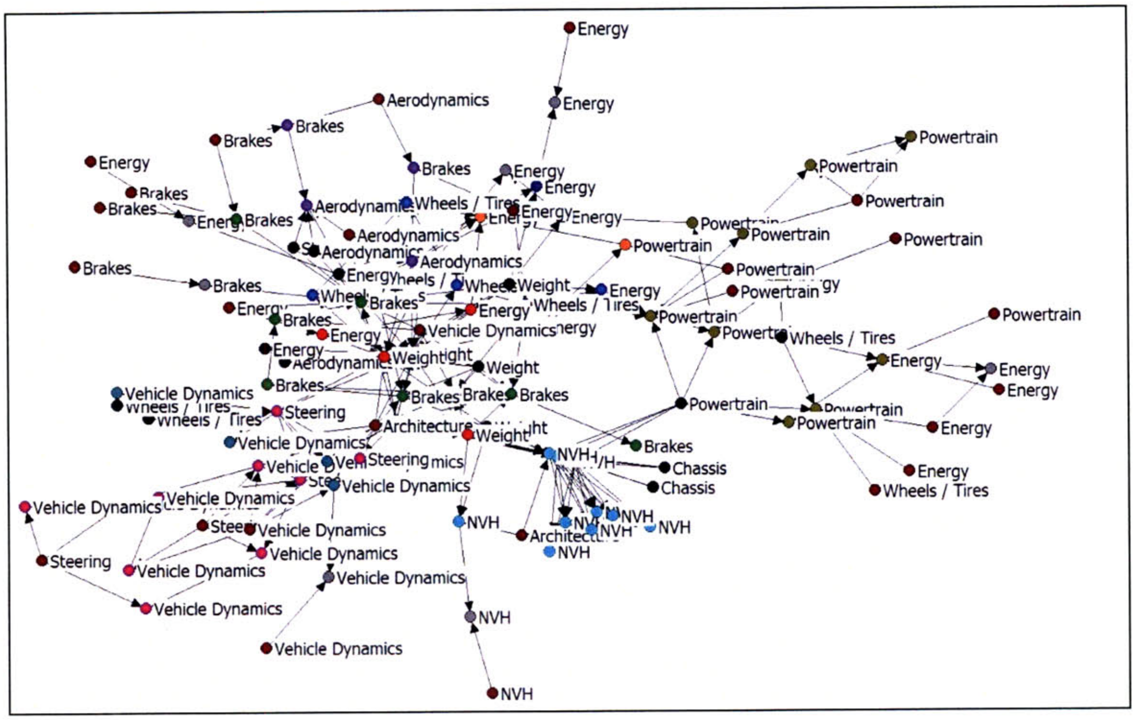

Figure 25. Theoretical sociogram of systems (engineering team based)

The detailed measures from this social network (degree centrality, closeness and betweenness) are presented in the section *9.6* in the Appendix. However, some aspects of the network are outlined below:

- Estimating the degree centrality of the groups shows that *Energy* and *Weight* are the most central in the network with a degree of *69* and *67*, respectively. This basically means that these two groups have the greatest number of direct connections. This is driven because of the fact that a significant number of teams need input from them to perform their individual evaluations. The latter is demonstrated by their out-degree equal to *35* for all *Energy* variables and *41* for *Weight*, being the highest of the network. In theory, these teams should be recognized as the major source of information for the project.

- *NVH*- and *Brakes*-related variables add up the highest in-degree with *44* and *43* respectively, meaning that they require interacting with a considerable number of modules to get the information needed to evaluate the design. Interestingly, *Weight* has a relatively low in-degree (equal to *26*), meaning that it provides much more information than it receives.

- Regarding in-closeness and out-closeness, *Energy* is by far the team with the highest figures with *24* and *23.9*, respectively (*Vehicle Dynamics* shows the second highest in-closeness with *16.6* while *Powertrain* is second for out-closeness with *14.3*). This would mean that *Energy* should be in a position (e.g., organizational, physical, etc.) that can allow it to be close to the rest of the engineering teams.

- *Energy* and *Weight* teams show the highest betweenness with *657.7* and *560.5*, respectively. This means that the both of them serve as the link for other groups and a significant amount of information flows through them. Referring to the basics of social network theory, these two teams could be perfect *linchpins*. In theory, these two teams could control the information reaching different parts of the network. In fact, during a multi-attribute optimization, either of these two teams could take the lead in coordinating the efforts of the various engineering teams (it will be discussed in the coming sections that the *Weight* team does play an important role in organizing several groups, especially during the final phases of the design, to minimize the weight of the car).

5.3. Construction of the Resultant Actual Sociograms

The actual social networks for Phase I and II are introduced in *Figure 26* and *Figure 27*, respectively (it should be noticed that the labels of the nodes correspond to the engineering team to which they belong; for the sociograms showing the ID of each engineer, refer to the *Appendix* section *9.10*). There are some assumptions that were taken to build up the sociograms:

- The networks were constructed by applying the survey to the engineers responsible for the systems concerned; consequently, their responses were not limited to these systems and it can be noticed that actors belonging to a great variety of teams appeared in the sociograms (e.g., program management, manufacturing, marketing and purchasing, to name a few).

- Not all the teams shown in the sociograms will be analyzed in detail; the main focus will be on the teams pertaining to attributes and systems decomposed in the previous section. However, based on conversation with a few engineering managers, it is assumed that some of the patterns of interaction of those analyzed could be extrapolated to other teams.

5.3.1. *Actual Sociogram - Phase I*

The sociogram shown in *Figure 26* displays three *social clumps* [5] as highlighted by the blue, gray and orange ovals. These clumps are completely isolated from the rest of the network and the reason for this, as concluded after interviews with some actors, is that they are *application teams,* which means that they are responsible for making some minor customization of pre-designed products to meet the specific needs of some low volume markets.[14] The individuals belonging to the clump within the orange oval were evaluating the introduction of the vehicle into Africa and the Asia-Pacific markets including countries such as Thailand and South Africa; the clump in the gray oval was evaluating the sales strategy for Taiwan; the actors inside the blue clump were assessing some specific components for the Japanese markets. The way these clumps get connected to the rest of the network is by some ties to the Purchasing and Marketing teams, who were not interviewed during the research.

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[14] This customization could be done to ease the manufacturing process in a particular facility or to define the sales strategy, among other reasons.

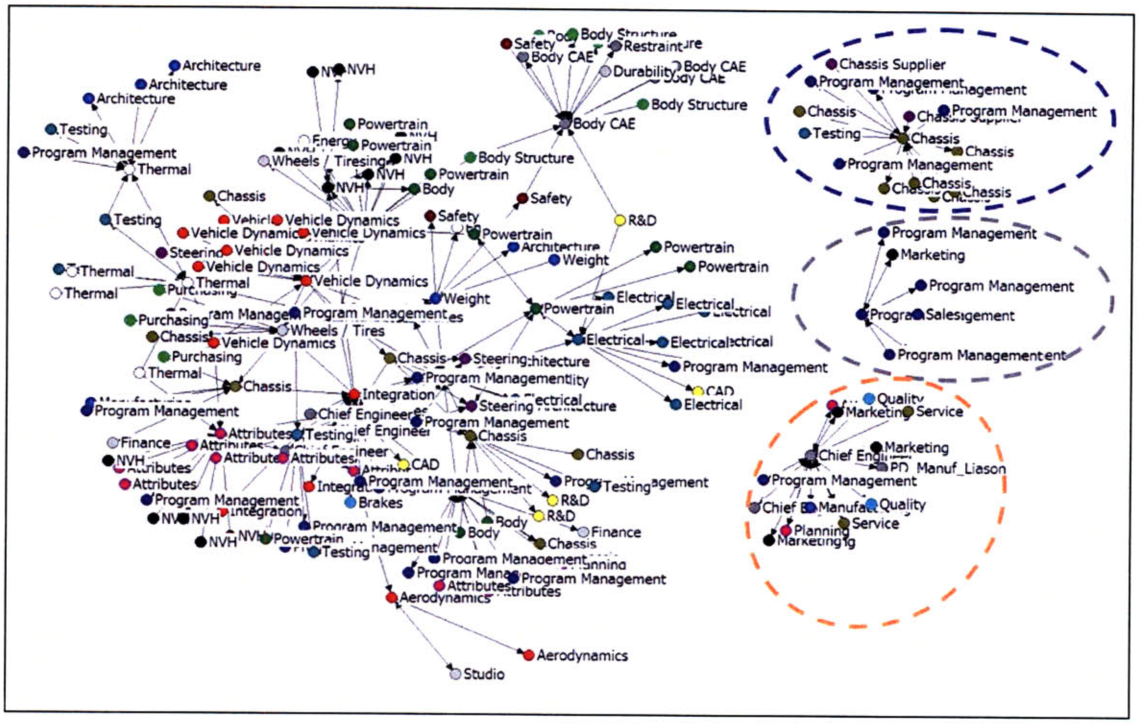


Figure 26. Sociogram of Phase I based on engineering teams

The colors in the sociograms of *Phase I* and *II* represent different engineering teams, which can be recognized referring to *Table 8*:

🟥	Aero	🟫	NVH CAE	⬛	Marketing	🟫	Service
🟦	Architecture	🟦	PM	▨	PD_Manuf_Liason	🟪	Steering
⬛	NVH	🟫	Chassis	🟥	Planning	▨	Studio
▨	Chief Engineers	🟪	Chassis Supplier	🟩	Powertrain	🟦	Testing
🟥	Attributes	▨	Durability	🟩	Purchasing	⬜	Thermal
🟩	Body	🟦	Electrical	🟦	Quality	▨	Wheels / Tires
🟩	Body Structure	⬜	Energy	🟨	R&D	🟥	Vehicle Dynamics
🟦	Brakes	▨	Finance	▨	Restraint	🟦	Weight
🟨	CAD	🟥	Integration	🟫	Safety		
▨	Body CAE	🟦	Manufacturing	🟦	Sales		

Table 8. Color symbology for actual sociograms

The measures of the sociogram are presented in section 9.7 of the *Appendix*; a few items that are worth describing are listed next:

- *Attributes* is the team with the highest degree centrality, with *67*. This can be explained by the fact that they must directly monitor and integrate the deliverables of several attribute teams to make sure a feasible design can be delivered. In fact, the team's out- and in-degree also appeared to be the highest of the network (*46* and *49*, respectively). Given the number of direct interactions with diverse teams, *Attributes* could potentially be the one leading the efforts of an integrated multi-objective optimization (e.g., vehicle dynamics, NVH, weights, etc.). Unfortunately, as of now, this doesn't occur, at least not from a multi-attribute perspective and whatever optimization takes place (mainly weight) happens late in the program (during *Phase II*).

- *Program Management (PM)* is by far the team with the highest in- and out-closeness of the network (*18.16* and *17.16*, respectively). This is well explained by the influence that PM exerts on the teams in terms of resources and timing. During the concept definition, PM must guarantee that the selected solutions are affordable and achievable under the given timing; therefore, their influence in some direct ties (e.g., teams responsible for vehicle level deliverables) must spread to other PD teams (e.g., those responsible for component- and system-level deliverables). For this same reason, the *Attributes* team is second from the top with an in- and out-closeness of *9.95* and *10.85*, respectively.

- *Attributes* shows the highest betweenness with *9,416* for the reasons explained in the previous bullets; these make them important *linchpins* of the network. This would support the idea of having this team being responsible for integrating the optimization efforts of different engineering teams, especially at this phase of the program where there is significant flexibility to make relatively ambitious changes in the design. It is interesting also to see that *Brakes* is second in betweenness because, indirectly they are affected by several engineering teams (e.g., weight, vehicle dynamics, etc.).

5.3.2. *Actual Sociogram – Phase II*

The sociogram for *Phase II* (see *Figure 27*) also shows a couple of clumps encircled by the orange and blue ovals which mimic those introduced in *Phase I's* diagram. It can be noticed that the "gray" clump doesn't appear in the new sociogram given the fact that being closer to the launch required further interaction with some other areas of the PD organization. As mentioned before, the orange and blue groups are probably connected to the social network by some actors that were neither surveyed nor referenced during the study.

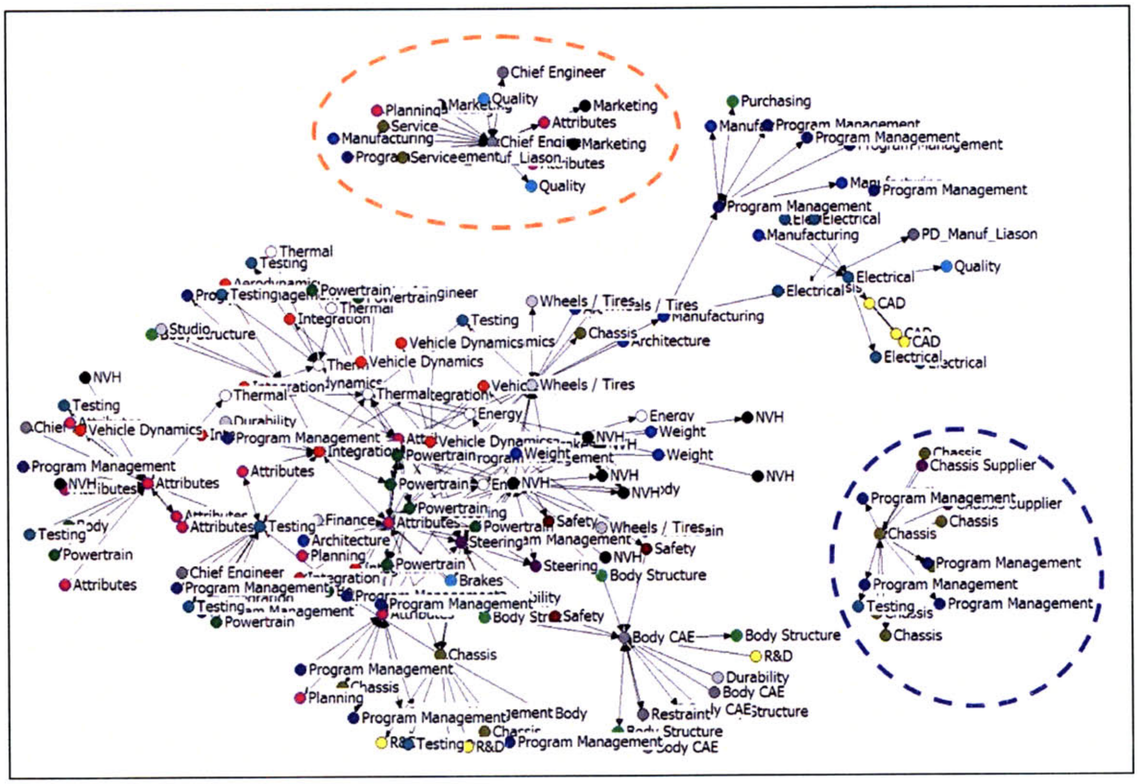


Figure 27. Sociogram of Phase II based on engineering teams

Using the measures presented in the *Appendix* section *9.7*, some interesting behaviors can be observed from the network:

- Just like in *Phase I*, and for the same reasons, *Attributes* tops the list in terms of degree centrality with *75*, and also in out- and in-degrees (*57* and *56*, respectively). Interestingly, comparing the relative degrees of the first and second phases for this team (*CD': 30.2 vs. 33.8; Out-: 20.7 vs. 25.7; In-: 22 vs. 25.2,* respectively), *Phase II* shows a slight increase because as the due date for freezing the design gets closer, more discussions must take place to solve any unresolved concerns.

- *Program Management* and *Attributes* top the closeness index in the second phase and they show similar figures to their respective *Phase I.*

- *Attributes* is again high in betweenness (*8,348.7*) but iinterestingly, *Brakes* went down in the list significantly (from 2nd to 17th). In particular for the *Brakes* team this was because it was during the first phase where several of the elements influencing braking performance were undefined and more discussions needed to take place; on the other hand, during the second phase brakes engineers were more concentrated in executing an assumed design and therefore, more tasks could be performed independently.

5.4. Comparison of the Theoretical and Actual Social Networks

So far, generic descriptions of the three networks (theoretical, actual Phase I and actual Phase II) have been developed. Nevertheless, as stated before, in order to identify if the organization under analysis has barriers that preclude a proper environment for the multi-objective optimization, performing a comparison between the theoretical and actual networks becomes relevant.

It is proposed that the comparison of the theoretical and actual networks to be performed using as a reference some of the engineering teams encountered in the theoretical network. It should be noticed that none of the theoretical sociograms presented in this section are time dependent because they don't deal with the time required to develop the systems or attributes. Hence, they just show the interactions that should be continuously taking place to achieve an optimized design.

5.4.1. *Aerodynamics*

In order to compare the social networks, it is proposed to start analyzing the direct ties of each engineering team; these are displayed in *Figure 28*. It must be noticed that none of the theoretical sociograms are time dependent for it is based on the mathematical relations between variables and does not take into account the tasks actually required to perform any design evaluation (e.g., modifying drawings, performing computer evaluations and package studies, develop physical prototypes and tests among others).

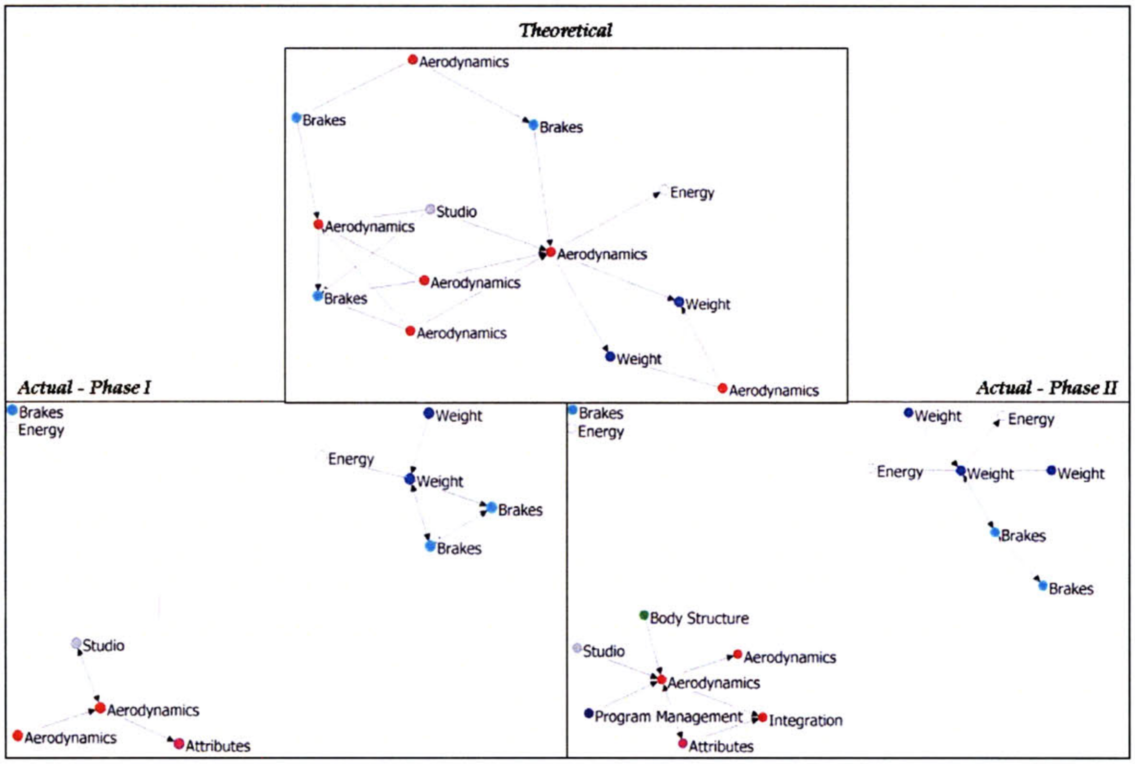


Figure 28. Comparison of the direct ties of the Aerodynamics Team

In principle, the theoretical sociogram shows that the *Aerodynamics* group should be in direct interaction with the *Brakes, Energy, Studio* and *Weight* teams; however, some discrepancies occur in the actual sociograms:

- First of all, *Aero* doesn't interact directly with either *Weight* or *Brakes*. After some discussions, this interaction doesn't take place directly because the influence that the Aero-related variables have in these two groups is not significant. This is also confirmed by the relative sensitivities presented on the tables in section *9.5*. In *Table 21*, it can be seen that the objective *Brake Distance Factor* shows a sensitivity of *0.1* with respect to the aerodynamic design variables (the higher relative sensitivity of this objective is with respect to a *Weight* variable, equal to *0.6*). In *Table 22*, it is observed that the weight at the front and rear axles show a relative sensitivity close to zero with respect to the aerodynamic design variables. Because of this, it can be understood that any cross-communication required between these three teams takes place through intermediaries such as the *Attributes* and *Integration* teams as shown in *Figure 29*. The need for intermediaries by *Aero* is also reflected in its low relative betweenness, especially in the actual networks (*Theoretical: 3.2; Phase I: 1.7; Phase II: 2.8*).

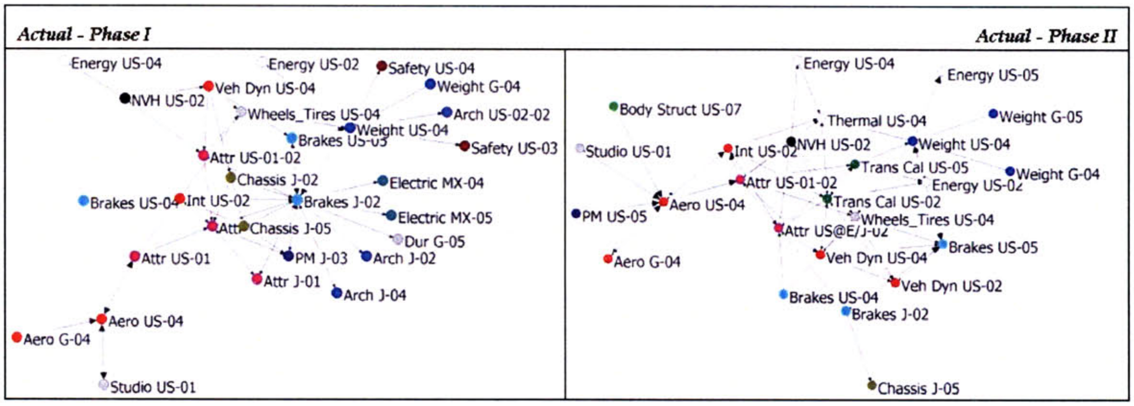
- *Aero* doesn't show any direct tie with *Energy* even though the relative sensitivity of the *Speed Factor* (handled by later) with respect to the drag coefficient is high (*Table* 23 shows a value equal to *0.7* implying a *strong* tie). This lack of connection can be attributed to two causes:
    - During *Phase I*, the German site had the lead of the aerodynamic development of the vehicle and NA was just supporting the work in terms of some specific requirements. It could be noticed from *Figure 29* that in *Phases I* and *II*, the European and NA engineer do show a tie (labels on this figure display the ID of each engineer; for further information about the meaning of these labels refer to the Appendix in section *9.10*). Accordingly, since most of the decisions were being taken by Germany, the assigned NA engineer was also working in other projects and this precluded his interaction with other teams such as *Energy*. In fact, at some instances, the NA and German *Aero* engineers themselves were confused about the ownership of the aero-related development of the NA variant. Consequently, information sharing between *Energy* and *Aero* was constantly performed through an intermediary.

- The *Energy* team didn't communicate directly with the Aero engineer in Europe as the former typically looked for any cross-functional information within the NA organization. In fact, sometimes they didn't have a clear idea on who was the right person to contact in the European site because of a lack of knowledge about how the organization was structured.

- In *Phase II*, the aero-related responsibility was shifted to NA but since most of the design was already frozen, no significant communication took place with the Energy team.

The difference of direct connections between the theoretical and actual networks is also reflected in the relative degree centrality which is significantly lower for the former (*CD′: 19.8 vs. 1.8 & 3.15; Out-: 12.6 vs. 1.8 & 2.7; In-: 7.2 vs. 1.8 & 3.15*).[15]

- In the actual sociograms, *Aero* did interact with *Studio* in both phases. During the second phase they also communicated with *Body Structure* because most of the designs proposed by the *Studio* were actually being brought to a manufacturable level by the former.


Actual - Phase I

Actual - Phase II

Figure 29. Indirect ties of the Aerodynamics Team

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[15] The first value of each triad of numbers belongs to the theoretical network, the other two belong to the actual networks in *Phases I* and *II*, respectively.

Three conditions can be concluded from analysis on the *Aero* team:

a) When the sensitivity of the parameters is low, information sharing is performed through intermediaries.

b) Geography didn't seem to be an obstacle in the interaction of the two Aero engineers (it wasn't ideal, but it wasn't prohibitive); however, it did seem to be a barrier between the *Aero* engineer in Europe and the *Energy* team in NA. Sometimes this is promoted by the lack of understanding on how the European site was organized.

c) Using the definition introduced in section *3.4.1*, the *Attributes* team is the *linchpin* that connects *Aero* to other nodes where information sharing is needed.

d) Shifting the responsibilities from one site to another at the middle of the project doesn't seem to be an ideal condition for MSDO. This is especially evident when the lead engineer is located in a site different from the other teams during the first phase, where the early learning should take place and there is more design freedom.

5.4.2. Brakes

Figure 30 shows the theoretical and actual sociograms for the *Brakes* team. First, it is worth comparing the two actual sociograms:

- *Brakes* shows an evolution between *Phase I* and *II* showing significantly more direct interactions in the former *(CD': 8.11 vs. 4.5,* respectively). The reason behind this is that it is during the first phase where most of the design elements that affect brakes are defined such as the vehicle architecture and dimensions; besides, the initial weight assumptions are performed in this phase too. In the second phase, the main interactions occurred with *Weight, Vehicle Dynamics* and *Wheels / Tires* because the design gets refined and there are some variables that

Brakes team can define once more specific information is available. This should explain the drop in relative betweenness from *19.62* in the first to *1.1* in the second phase.

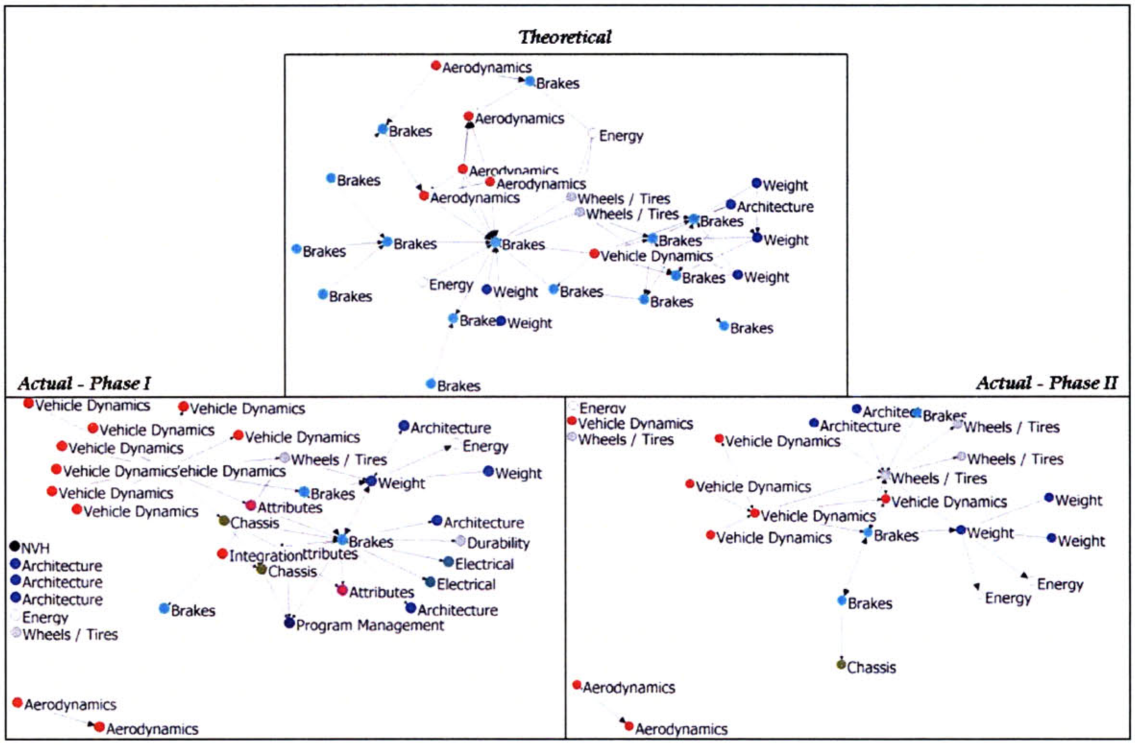

Figure 30. Comparison of the direct ties of the Brakes Team

- An interesting fact of this project was that the lead of the brakes development was originally in Japan and afterwards it was shifted to the US site (similar to what happened with the *Aero* team). This is reflected in the number of direct ties that the engineer located in Japan (red circle in *Figure 31*) had compared to the US engineers (blue circles in *Figure 31*) during the first phase; this trend was then reversed for the second phase. This is confirmed by the shift in the degree centrality measures of each engineer shown in the following table:

	Node Label	Location	Degree (CD)	Relative Degree (CD')*	Out-Degree	Relative Out-Degree*	In-Degree	Relative In-Degree*
Phase I	Brakes J-02	Japan	14	6.306	14	6.306	12	5.405
	Brakes US-04	US	1	0.45	0	0	1	0.45
	Brakes US-05	US	3	1.351	2	0.901	3	1.351
Phase II	Brakes J-02	Japan	3	1.351	3	1.351	1	0.45
	Brakes US-04	US	2	0.901	2	0.901	0	0
	Brakes US-05	US	5	2.252	5	2.252	5	2.252

Table 9. Degree centrality for Brakes engineers (Actual Networks)

Apparently, from some conversations with team members, the low degree centrality of the US engineers might have been the reason of minimal direct interaction between *Brakes* and *Wheels/Tires* in the first phase; any tie between these two teams was with *Attributes* as an intermediary. Unfortunately, due to the interactions presented in the engineering analysis plus packaging considerations, it would be desired to have them interacting directly from the very beginning and not just during *Phase II*.

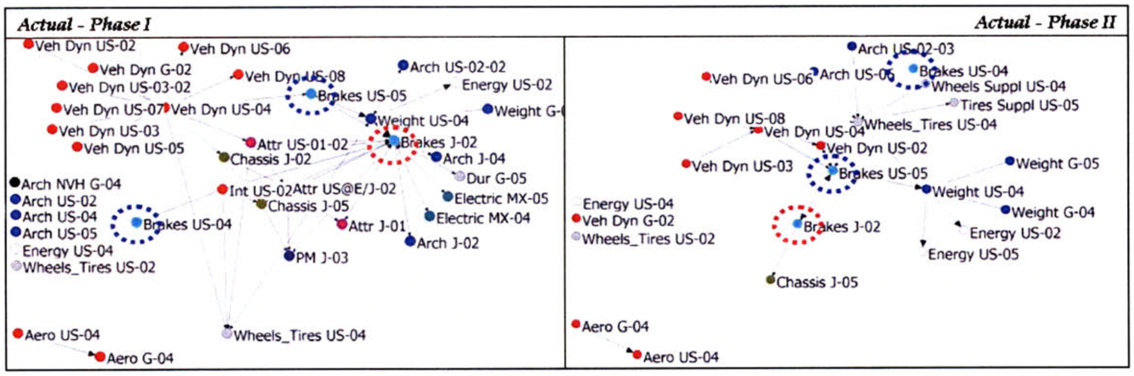

Figure 31. Comparison of the actual interactions of the Brakes Team

- Comparing now the theoretical and actual sociograms, just as indicated in the previous section, *Brakes* and *Aerodynamics* do not show any direct interaction because both teams are not deemed to have a significant influence on each other.

- During the first phase, *Brakes* doesn't show a direct interaction with *Wheels / Tires* and any connection was thanks to the *Attributes* team. This was partially influenced by the fact that, at least at the beginning of the project, the lead for the development of brakes was in Japan, while the tires and wheels were implemented in the US.

- *Brakes* and *Energy* don't show any direct link in the actual sociograms as compared with the theoretical one. Apparently, the sensitivity of the variables to be shared by these two teams is low, representing a *weak* tie and it does make sense not to show a direct interaction (refer to *Table 21*, where the relative sensitivity of the *Brake Factor* with respect to the design variables handled by *Energy* is below *0.1*).

- Taking a look at the measures between the theoretical and actual sociograms, they don't show a close correlation. This could be due to the lack of connections already discussed plus the presence of the *Attributes* and *Integration* working as *linchpins*.

Summarizing, some of the highlights of the *Brakes* team are:

a. During the first phase, it shows a good level of direct interactions with the teams on its site which fosters the early learning described by the MDO strategy.

b. For the reasons explained in the analysis of the *Aerodynamics* team, shifting the responsibilities from one site to another at the middle of the project doesn't seem to be an ideal condition for MSDO.

5.4.3. Energy

Probably the greatest difference in the theoretical and actual networks appears in the *Energy* team.

- It is evident from *Figure 32* the significant difference in direct ties that the networks show which means that most of the information sharing was through intermediaries in the actual sociograms. While in the theoretical network *Energy* shows the highest relative degree centrality with *62.2* (*31.5* and *30.6* for relative out- and in-degree, respectively) meaning is the one directly interacting the with the greatest number of engineers, the actual networks show very low numbers (for *Phase I CD': 0.9,* rel. out-degree: *0,* rel. in-degree: *0.9;* for *Phase II CD': 2.70,* rel. out-degree: *1.35,* rel. in-degree: *2.25*). This indicates that any information required by *Energy* had to come from an intermediary.

- It is relevant to mention that by the end of the second phase, the *Energy* engineers realized that the vehicle's transmission required internal changes to meet one of the desired gradability requirements. This should explain the direct interactions that *Energy* shows with *Transmission* engineers (which are part of the Powertrain team) in the actual sociogram for *Phase II* in *Figure 32*.[16] One interesting behavior observed in this event was that when the *Energy* engineers became aware of the possibility of not meeting the requirement, it took them a while to communicate with the transmission engineers. The reason for this was that they decided to perform several evaluations to make sure their estimates were right. Interestingly, this condition of delayed communication was recurrent during conversations with engineers from other areas. This could be an area for improvement in the PDP because the more it takes for a change to be realized, the more the design freedom is reduced.

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[16] By the time this report was created, there were still discussions between both teams about the way the gradability requirement could be met.

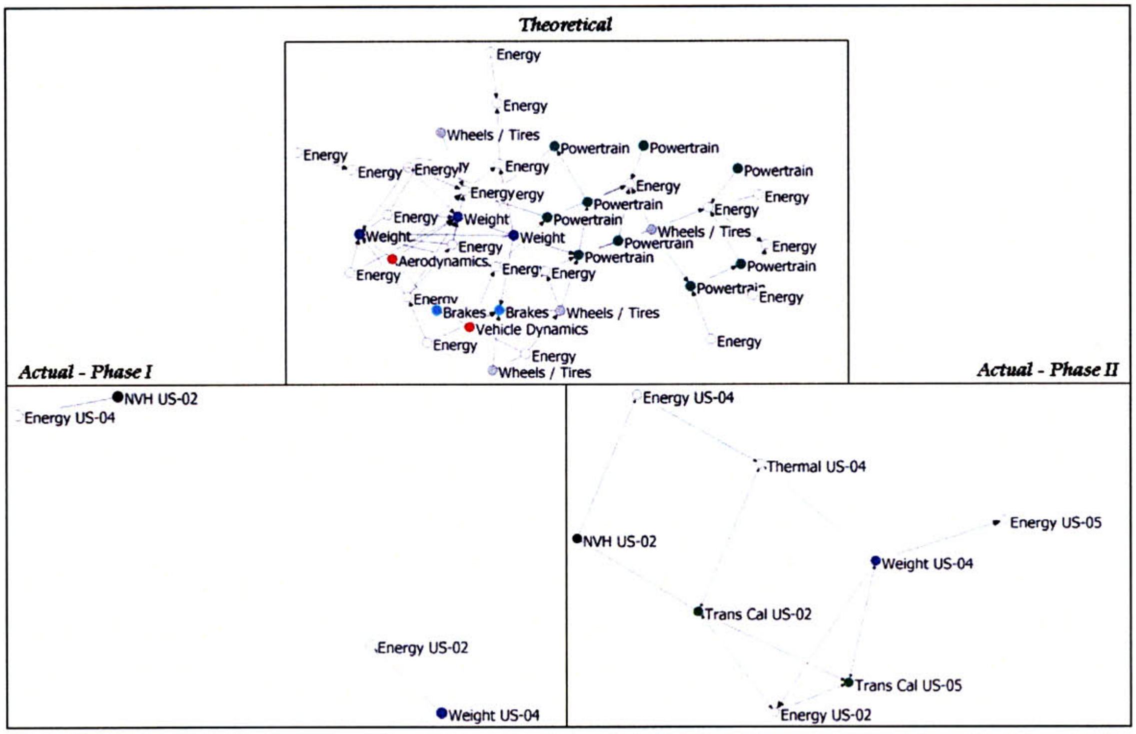

Figure 32. Comparison of the direct ties of the Energy Team

- When the *Attributes* team is added to the actual sociograms, we can see that *Energy* gets connected to most of the engineering teams anticipated by the theoretical sociogram (except for the powertrain engineers in the first phase). It can actually be said that the role of *Energy* in the theoretical sociogram as the central actor of the network, is actually taken by attributes (this is also confirmed by the high difference in closeness and betweenness of the three networks). One of the reasons for this was that several variables handled by *Energy* were already defined during the development of the Japanese and European vehicles. Consequently, its main function resided in monitoring the changes performed by other teams which, in theory, could be achieved by interacting mainly with *Attributes*.

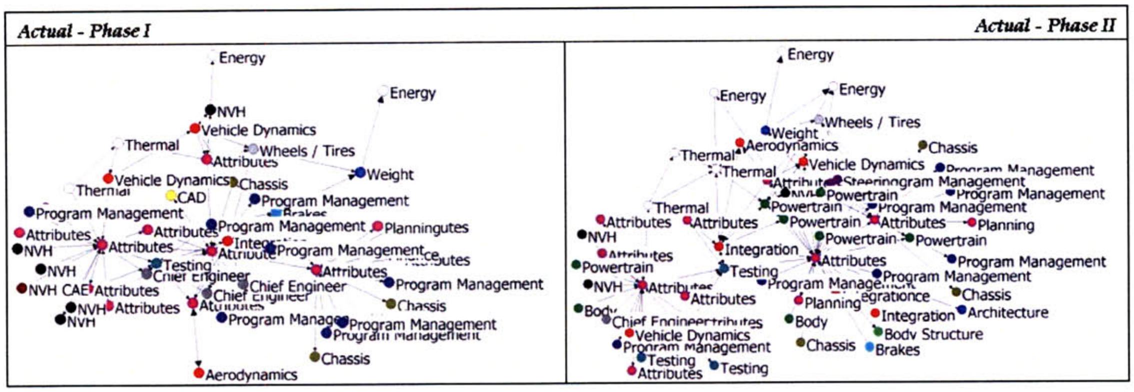

Figure 33. Comparison of the actual interactions of the Energy Team

One main idea was extracted from the analysis of this team:

a) There appears to be a recurrent behavior of not sharing information among teams whenever the initial assumptions of the project seem to require changes. It is after the team in need of the change is absolutely sure that it is required when the information is cascaded to the proper stakeholders; once this occurs, interactions among them increase significantly.

5.4.4. *NVH*

The sociograms showing the direct ties of the NVH engineers are presented in *Figure 34*.[17] It is important to mention that for this case, the main focus regarding NVH was on the ride of the vehicle; other NVH-related areas (e.g., wind noise, structural stiffness, etc.) were not analyzed. Some highlights of the comparison are:

- The theoretical sociogram shows that the *NVH* team should be interacting with *Weight*, something that is not shown in the actual sociograms. However, there is a simple explanation for this: the questionnaire asked for the people whom engineers had to interact with the most. *Weight* is a team that needs to provide information to basically all teams; however, in the case of *NVH*, it is only at

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[17] It is important to mention that for this case, the main focus was on the ride of the vehicle; other NVH-related areas (e.g., wind noise, powertrain NVH, structural stiffness, etc.) were not analyzed.

specific milestones that engineers request an update on the weight status of the vehicle. In other words, the weight information is not a variable that is continuously updated in NVH studies, but just at specific times during the duration of the project. Therefore, while it is not a frequent link, *NVH* and *Weight* engineers do interact when needed.

The weight variable is not daily updated in NVH evaluations, like CAE analyses, because engineers tend to perform A-to-B comparisons. These comparisons are intended to evaluate how a particular change affects the behavior of the system; therefore, the variables modified between two analyses must be controlled in such a way that their influence in the design can be easily identified. Modifying the weight in every single study wouldn't allow understanding the causes of a particular behavior; therefore, it makes sense to freeze it for a considerable amount of design iterations.

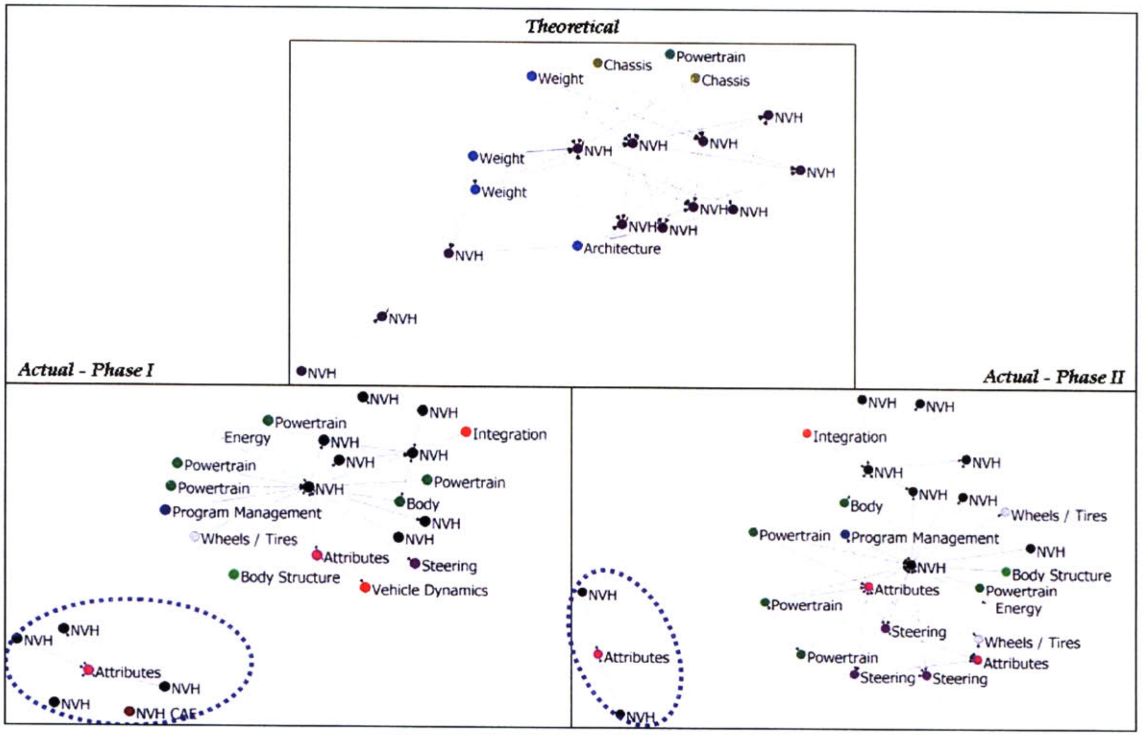

Figure 34. Comparison of the direct ties of the NVH Team

- The actual sociograms show one clump each highlighted by the blue circles. The engineers inside them are located at the German site and they are linked to the NA organization by the *Attributes* team mainly through engineer with ID *Attr US@E/J-02* highlighted in the red oval on *Figure 35* (based on the label coding of *Section 9.10*, he was an *Attributes* supervisor from the US site, but temporarily located at Europe and Japan). This engineer was critical for linking not only *NVH* engineers, but also several engineering teams distributed all around the globe. Proof of this was that he showed the second highest individual relative betweenness for the first phase and the highest for the second with *11.1* and *14.5*, respectively.

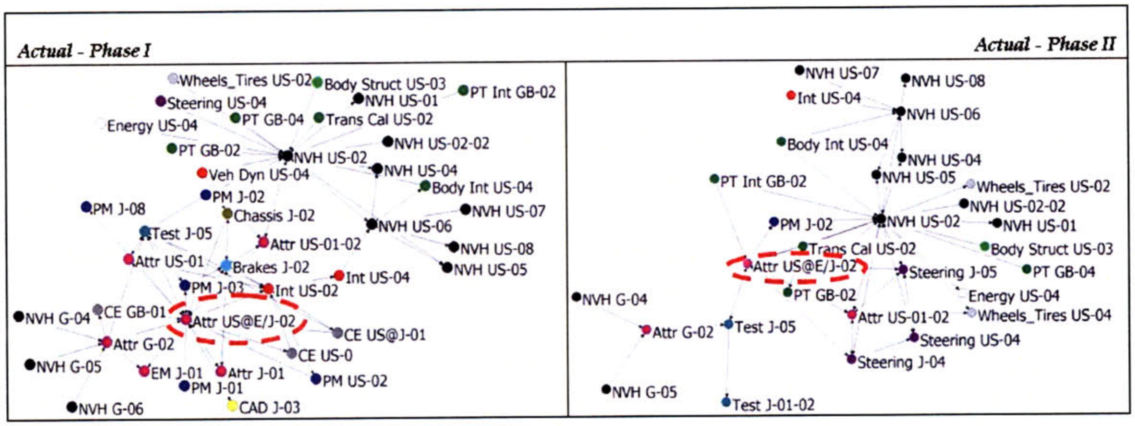

Figure 35. Ties of isolated social clumps with the rest of the NVH network

- One final remark about this group can be highlighted in both actual sociograms: there is a central *NVH* supervisor in the US site *(NVH US-02)* who clusters together the rest of the US NVH engineers. While this is expected because of his role as a supervisor, what is interesting is that, compared to his subordinates, he shows a high interaction with actors outside from his group. Under this condition, he becomes either an information "broker" or a "gatekeeper" and his team relies significantly on him to get information about the project (clearly, this is a *structural hole*).

Three main ideas can be highlighted from this analysis:

a) While the theoretical sociogram might show the need for a specific interaction, this may not be needed on a frequent basis but just at specific timeframes during the PDP.

b) As confirmed by several studies and organizations, having engineers in global assignments might close the information site between dispersed sites.[5]

c) Some teams may rely significantly on a single individual (typically the leader) to access specific information or in some cases, even to take decisions. Nevertheless, sometimes giving more empowerment to other team members to take a more active role in his or her interactions with others might actually speed up the PDP for information may flow faster.[16]

5.4.5. Powertrain

Taking a look at the *Powertrain*-related sociograms below, the theoretical and *Phase II* networks don't show a significant difference in terms of the direct ties that powertrain engineers should have. The only gap is appreciated with the *Wheels / Tires* team, interaction that might have occurred through *Attributes* (this couldn't be confirmed during the research though). Nevertheless, an evolution in the interaction appears from *Phase I* to *Phase II*:

- Contrasting to what was expected *Powertrain* shows more ties during the second phase than in the first one. Based on the MSDO, more flexibility in the PDP occurs in the earliest phases and therefore, the greatest number of ties should have been observed by then. However, in this case, the major development of the powertrain was done in Europe (specifically Great Britain) and its calibration was performed by the engineers of each site to meet the needs of the local markets. Therefore, NA engineers started to allocate more resources when the responsibility was shifted to them.[18] Unfortunately, as mentioned during the analysis of the *Energy* team, due to concerns about the gradability of the vehicle, calibrating the transmission wasn't enough to meet the targets. Consequently, there was a need to modify internal hardware. This challenged the timing of the program and more tests were required during the last phases.

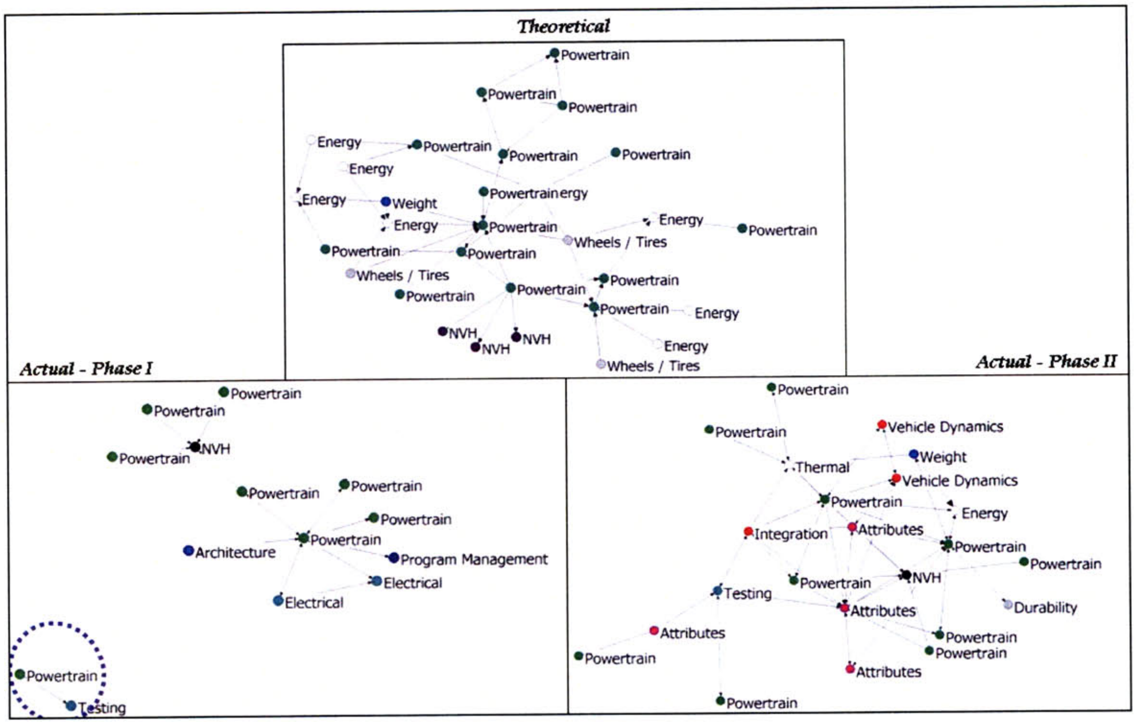

Figure 36. Comparison of the direct ties of the Powertrain Team

- The social clump in the first phase highlighted by the blue oval in *Figure 36* corresponds to engineers working in Japan for the needs of the local market; they were linked to the rest of the network mainly by *Attr US@E/J-02* who as highlighted in the previous section, is one of the most central actors (see *Figure 37*).

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[18] Some engineers from other teams mentioned that when the responsibility hasn't been shifted to their local site, they try not to get actively involved in the design for it can distract them from their current tasks.

- It is worth mentioning that *Attr US@E/J-02* was also central in the ties of powertrain engineers during *Phase II* connecting not only different systems but also the various sites.

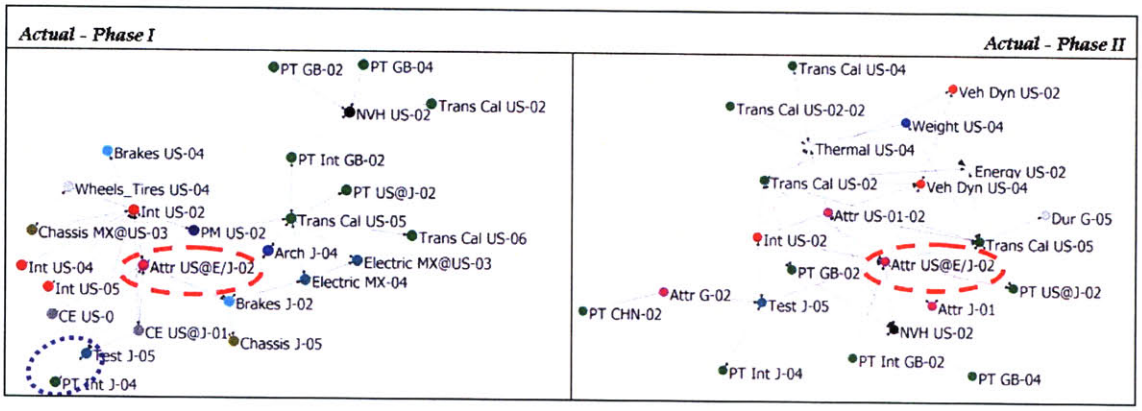

Figure 37. Ties of isolated social clumps with the rest of the Powertrain network

Two highlights already mentioned in previous sections can be outlined:

a) It was noticed again the importance of engineers in global assignment in linking international sites.

b) The shifting of the responsibilities from one site to another in the middle of the program might lead to unexpected changes in the design.

5.4.6. *Steering*

The reasons behind the differences between the theoretical and actual sociograms are described below (see *Figure 38*):

- A significant part of the steering system development took place in the Japanese site and then it was adopted by the European and US engineers with some minor modifications. In fact, just the teams requiring these modifications were the ones that actually showed direct interaction and this includes the Architecture and Safety teams in the first and second phases, respectively (the former were responsible for packaging the steering system into the vehicle). Consequently, several parts of the overall vehicle design were engineered around the given configuration of the steering system and other engineering teams are tied through intermediaries.

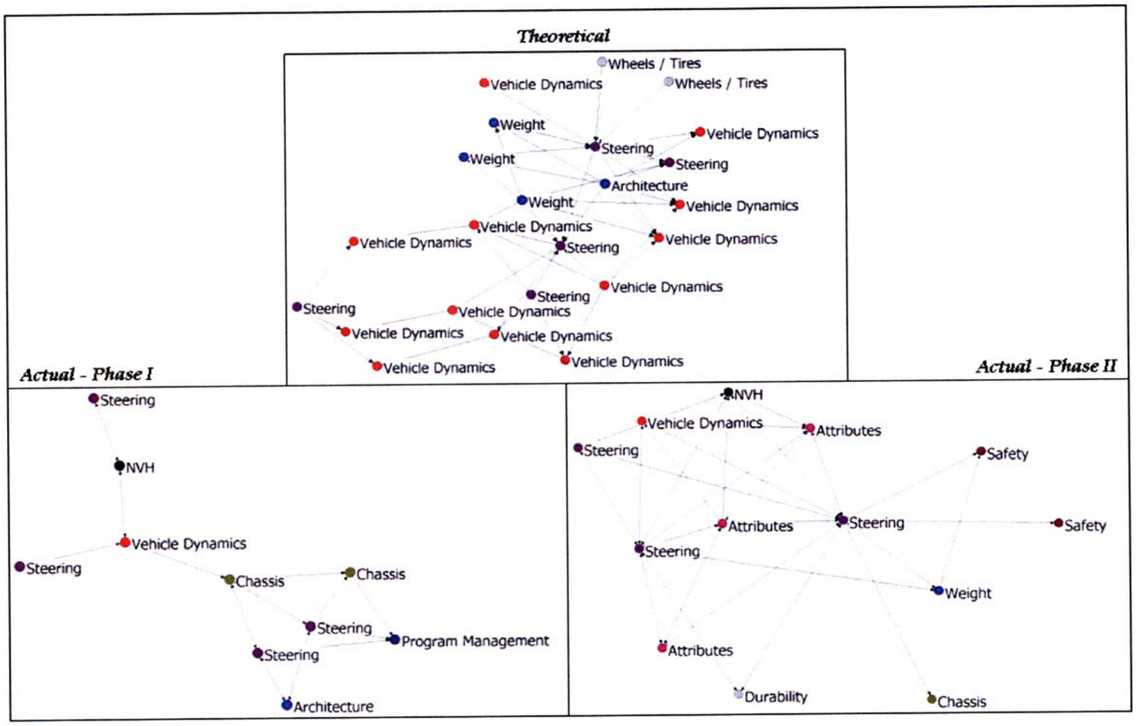

Figure 38. Comparison of the direct ties of the Steering Team

- The main intermediaries for the *Steering* team were *Attributes* and *Chassis*. The latter was responsible of releasing all chassis-related components and systems such as the steering, front and rear suspension, etc.; therefore, it made sense that this team served as the link between the *Steering* team and other stakeholders. I fact, for other vehicle systems, Design and Release (D&R) engineers interact with several teams and those could also play an important role in the MDO tasks (refer to *Figure 39*).

- On the other hand, *Attr US@E/J-02* was, again, a facilitator in transferring information between teams especially during the second phase when the implementation of the steering system took place (this also explains the evolution in the actual sociograms from the first to the second phase).

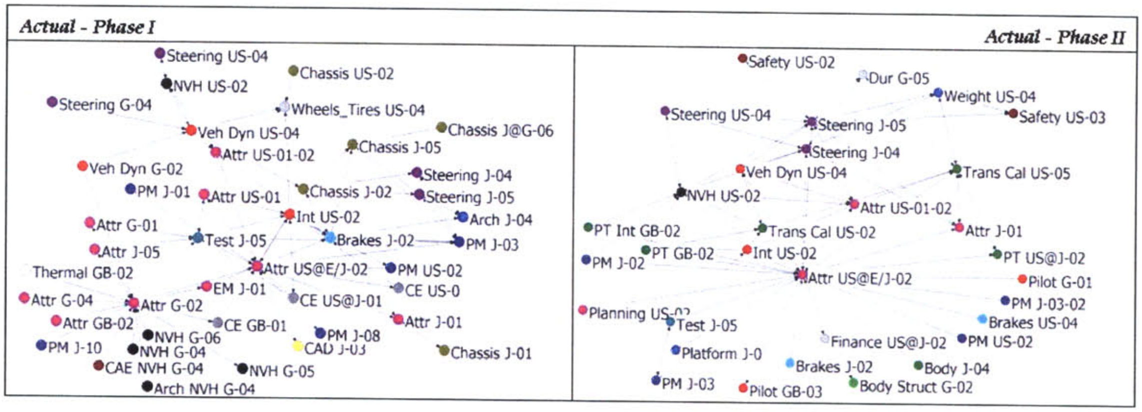

Figure 39. Comparison of the indirect ties of the Steering Team for the Actual Sociograms when some Attributes ties are added

Summarizing:

a) There are systems that can't be modified either because of the costs involved in changing them or because they are carry-over from other vehicles (this also allows capturing the value of economies of scale). As stated in *Chapter 3*, these systems could be considered as Parameters under the MDO methodology.

b) D&R engineers interact with cross-functional teams to deliver diverse components of the car; they could also become agents of the MSDO methodology if they are able to handle the information properly.

5.4.7. *Weight*

- In the theoretical network, *Weight* is supposed to be second in relative degree centrality with *64* and in relative betweenness with *9.2.*[19] Interestingly, it occupies seventh and sixth place in relative in- and out-closeness with *6.6* and *9.8*, respectively. The difference in centrality and closeness could be an indicator that

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[19] In fact, it is first in relative out-degree with 36.9.

most of the information shared with or by the *Weight* team should be through direct links and not through intermediaries.

The actual sociograms on the other hand show *Weight* with a low relative numbers (*Phase I: CD′ = 4.1, in-closeness = 1.7, out-closeness = 2.2, CB′ = 5.7; Phase II: CD′= 6.3, in-closeness = 1.7, out-closeness = 2.6, CB′ = 2.5*). This difference was already explained during the analysis of the *NVH* group: *Weight* tends to provide updates in the mass of the vehicle at specific milestones or when other engineers update their virtual or physical models after several iterations; consequently, some engineering groups omitted their interaction with the team during the surveys. Yet, *Figure 40* shows a good number of cross-functional ties between *Weight* and other teams.

- *Weight* tends to interact with more teams during the second phase than in the first because it is in the former when all the information of the vehicle is integrated and the aggregated mass is estimated. This leads to all teams to optimize the vehicle's mass which typically implies downgaging components by upgrading the material, or deleting non-critical parts. This is probably the optimization that makes sense to take place during the second phase of the project, i.e., when the architecture of the vehicle has already been defined. Nevertheless, the argument is that an effective MSDO should take place also during the first phase in order to aid in the definition of the overall product configuration.

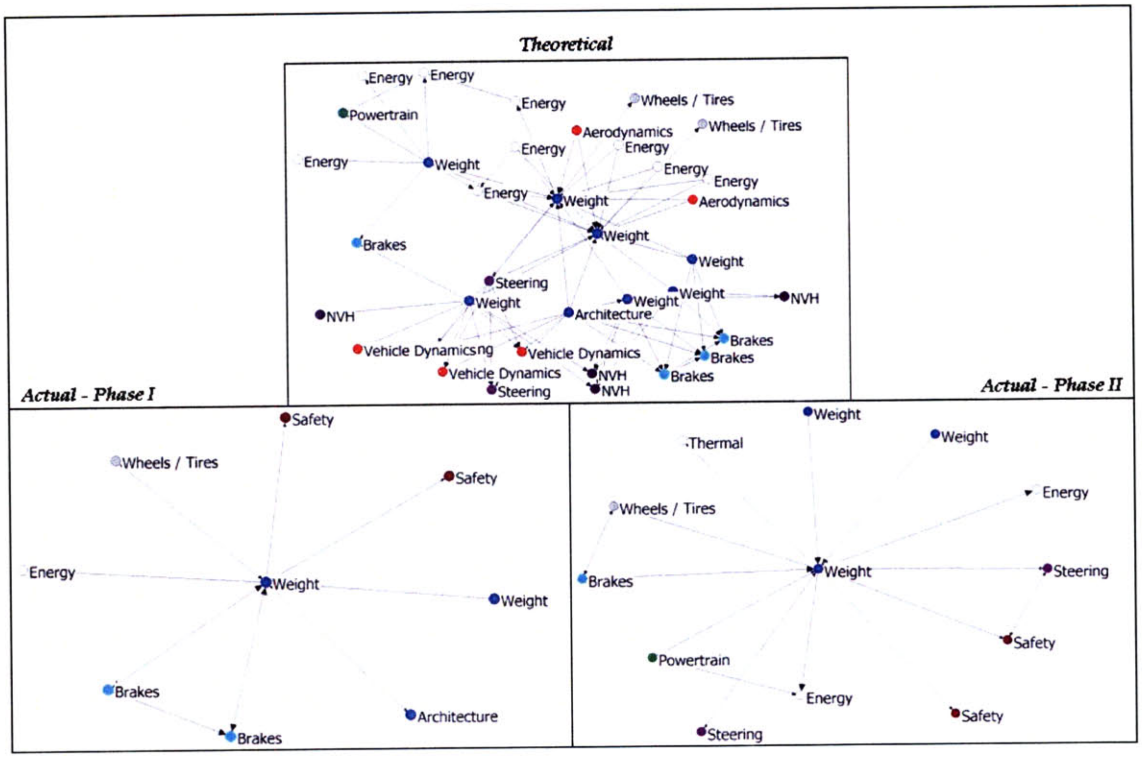

Figure 40. Comparison of the direct ties of the Weight Team

- One last observation from *Weight* is that this responsibility typically falls under a single engineer per site. This provides organizational clarity to the rest of the groups which makes them aware about whom to contact to get any mass-related specification. This clarity is not achieved by all teams and sometimes the lack of knowledge about the responsibilities of each team delays the PDP and precludes the MDO.

5.4.8. *Wheels and Tires*

Wheels and Tires shows a quite different situation from those presented so far:

- The overwhelmed *Wheels and Tires* was able to describe how his interactions evolved during the first and second phase. The tires of a vehicle are mostly developed by suppliers: any virtual simulations at a component level describing their behavior during the early phases of the design, is typically performed by them. The engineer working for the OEM is basically responsible for the design and release of the part, and therefore he must cascade the proper specifications to purchasers (e.g., weight) to make sure they select the appropriate supplier.[20] This continuous interaction with the supplier results in numerous ties with the *Purchasing* team in the actual sociogram of the first phase shown in *Figure 41*.

- The virtual models of wheels are quite complex due to the characteristics of the materials used; therefore, there are some limitations in estimating the actual behavior of the wheels and tires under different driving conditions. Consequently, it is during the second phase, when physical prototypes are available, that *Wheels and Tires* does interact with the several engineering teams. This permit to determine the previously uncertain behavior of the wheel under different driving conditions and for different attributes, namely NVH, vehicle dynamics, and weight as shown in the second phase in *Figure 41*. Interactions that should be taking place according to the theoretical sociogram, occur through the *Attributes* team in reality.

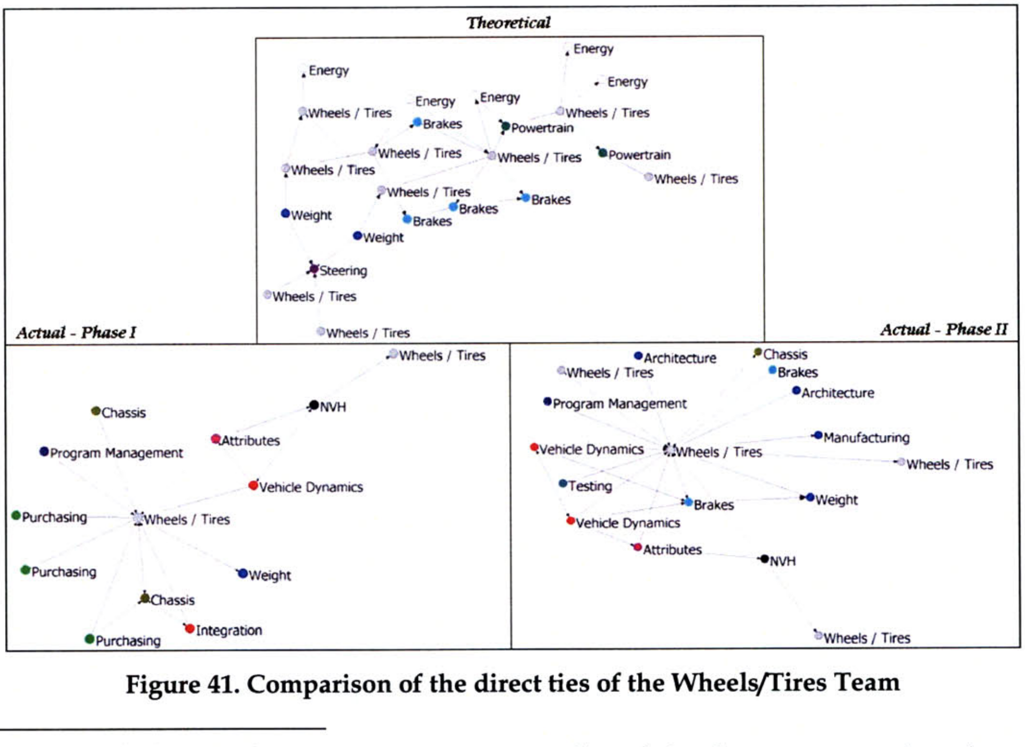

Figure 41. Comparison of the direct ties of the Wheels/Tires Team

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[20] The role of the Purchasing team was not evaluated in the present project; however, incorporating this into the analysis could allow identifying other areas for improvement in the PDP.

- Even though great part of the wheels development is performed by the supplier, it is actually the OEM's engineer who is responsible for interacting with the different teams within the organization. This explains the higher centrality measures of *Wheels_Tires US-04* (OEM engineer) with respect to the supplier *Wheels Suppl US-04* (see *Figure 42*). From an MSDO perspective, this could represent a challenge because the team actually engineering the component (the supplier), needs to interact through an intermediary with the rest of the PD organization. This condition is present in a great number of systems and components of the vehicle and not only the wheels and tires (e.g., seats, IPs, etc.).

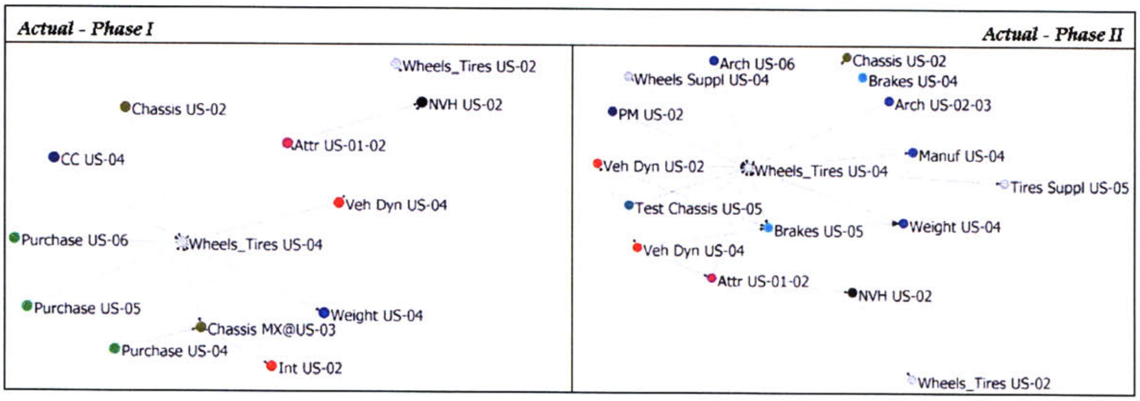

Figure 42. Comparison of the direct ties of the Wheels/Tires Team for the Actual Sociogram

Two ideas can be summarized:

a) There are some areas or components of a vehicle that still rely significantly on physical testing making it quite difficult to participate in an early MSDO due to the lack of physical prototypes.

b) Having suppliers engineering components and systems may represent an obstacle in sharing information directly with other teams. Therefore, having tools to understand how a system, component or attribute affects or gets affected by other areas becomes critical (e.g., *N^2 Matirx*).

5.5. Interaction between Virtual Analysts and Test Groups

As mentioned in *Chapter 3*, it is important to have an effective combination of virtual and physical tools (new and "traditional" approach [46]) for MSDO to work effectively. According to the manufacturer in this study, the development of a car goes through cycles where, first, intensive computer evaluations must be performed followed by a set of physical tests (at a component, system or vehicle level) as shown in *Figure 43* (the overlap between phases implies that as new data from tests are available, they are immediately used to update virtual models, and vice versa). These cycles start from surrogate models or prototypes (i.e., representations from previous projects) and go till the end of the vehicle's development when more representative models (both, virtual and physical) are available. Therefore, the interactions among these tools are critical to achieve an effective experimentation process (refer to *Chapter 3*).

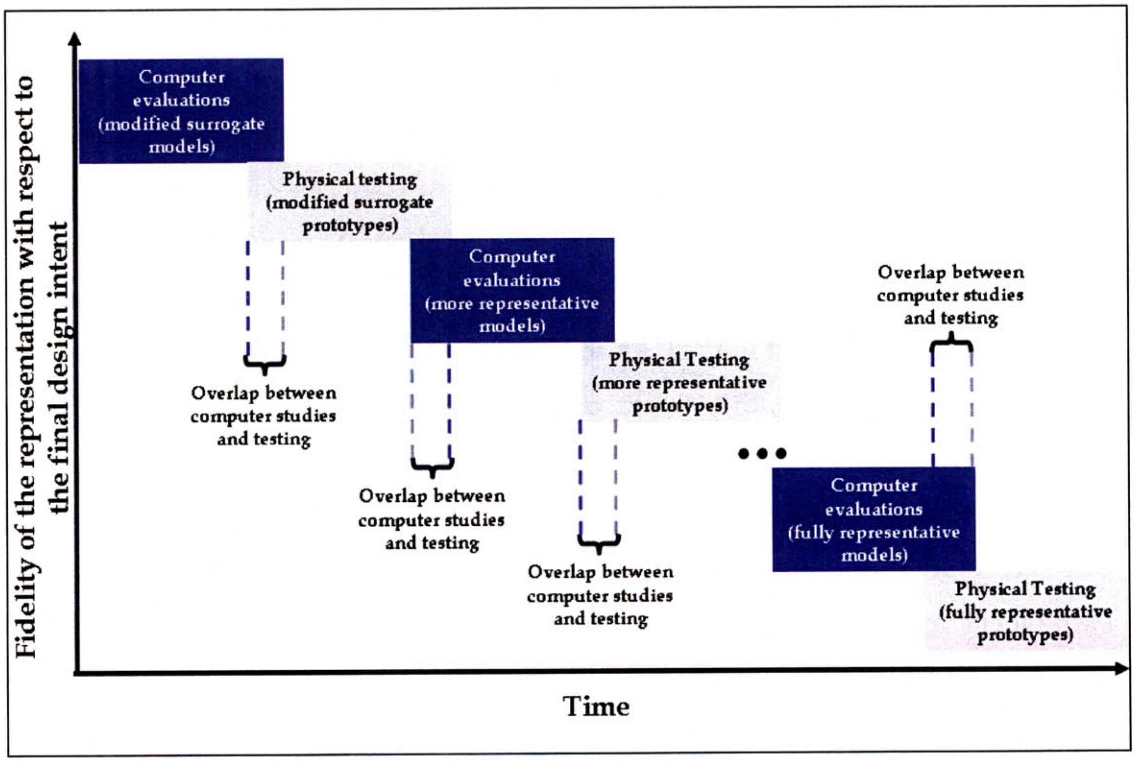

Figure 43. Cycles of computer analyses and physical evaluations

The objective of the present thesis is to identify elements that impede the PDP and in particular, the MSDO. Because of this, it was considered relevant to use the network information of two attributes (NVH and Thermal) to understand if there are some distinguishable patterns, at least from a qualitative standpoint, in the ties of those engineers conducting the physical development of the vehicle and those executing the virtual evaluations. The following figure shows a couple of sociograms in this regard:

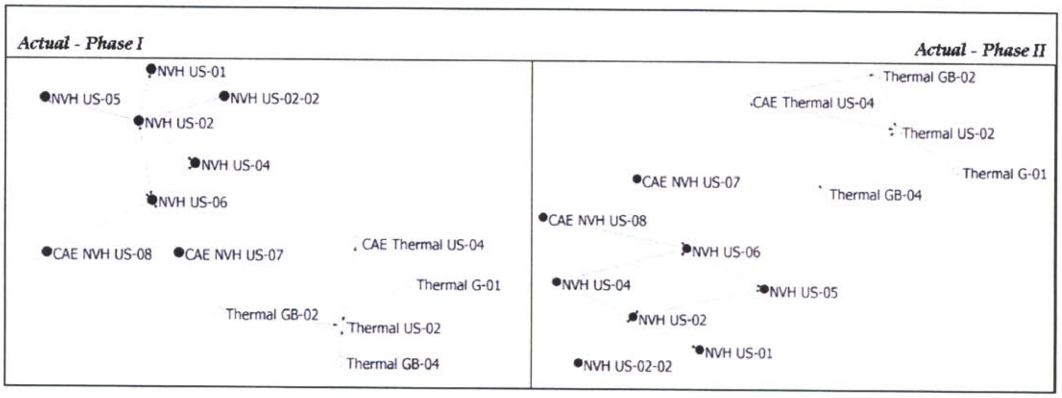

Figure 44. Ties between CAE and Development Engineers (NVH and Thermal)

Starting with the NVH team, in *Figure 44* it appears that CAE engineers (indicated in the sociograms with the *CAE* label) only interact with *NVH US-06* who happen to have experience in the use of physical and virtual tools.[21] While talking about this result with some of them, they agreed that not all development engineers[22] tend to interact with CAE engineers and this has led, at least on a few occasions, to misunderstandings in the information both teams handle. For example, it happens that physical tests don't fully reflect what was evaluated in the CAE models, or vice versa. In other circumstances, in the case of a design issue, they might work separated and not in an integrated effort, each trying to solve it with its own tools. While there isn't sufficient network data to see if this is recurrent in other teams, conversations with engineers do suggest it. From discussions, it appears that not all CAE and development engineers are fully aware of each others' methodologies; consequently, it makes sense to observe *NVH US-06* as the only actor connecting both capabilities.

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[21] In the sociogram of *Figure 44*, the interactions between the NVH and Thermal groups are not being analyzed; the interactions between the engineers of the same attribute are of concern in this section.

[22] In this case, development engineers are responsible for the physical tests.

In the case of the Thermal team, the CAE engineer (*CAE Thermal US-04)* was also responsible for the development portion. From discussions with engineers the sociogram in *Phase II* was more representative of the reality than that of *Phase I*; therefore, the latter can be disregarded. In this case, *CAE Thermal US-04* takes a role similar to *NVH US-06*.

One idea can be summarized, then, from the description above: It is obvious that connection of the test and computer analysts becomes effective in the presence of actors having knowledge of both environments.

5.6. Additional Comments

Along with the discussions presented above, there were a couple of factors that were continuously brought up during interviews with engineers and/or PD managers and which may have also contributed to some of the missing links in the actual networks when compared to the theoretical. The first one is related to the way the physical facilities are set-up; the second has to do with a difference in the virtual engines used among teams. It is thought that addressing these obstacles may bring some benefits in the communication of some teams, and consequently, to the PD process as well.[1]

With respect to the facilities, it is relevant to mention beforehand that most of the engineers of the present study belong to diverse functional teams. These teams are usually located close to other teams performing similar tasks (e.g., Body engineers of one project are next to others working for a different vehicle). Unfortunately, due to the size of the organization, it becomes difficult to have all actors located in a single facility and they are distributed throughout a considerably large campus. Hence, we might see Wheel engineers in one building and the NVH team in a different building across a boulevard. This limits the interaction frequency among both groups. Because of this, teams close to the *Attribute* engineers, for instance, might prefer to ask for or cascade information through them than by directly interacting with their counterparts from a different attribute. Translating this into the social network measures presented, this could be another reason why *Attributes* shows a high centrality.

Regarding the second item, it is interesting to see some conflicts that arise due to differences in the virtual tools used by the various teams. An ideal MSDO is intended to deal with different aspects of a design and therefore, a particular system can be analyzed from the point of view of different attributes. In reality, the tools required to evaluate these attributes are diverse and typically, different models representing the same system are required. For example, a set of heat shields surrounding the exhaust system of a vehicle must meet thermal, weight, stiffness, structural durability, manufacturing and cost requirements to name a few. If these heat shields are to be modeled using CAE/CFD/CAM tools, it will appear that, in order to evaluate each attribute, different software platforms might be required (e.g., the solver for heat transfer might be different to simulate the stamping process of the part). Along with this, the pre-processing of the virtual model might contrast too: the size of the finite elements might have to be different between the thermal and the stamping models, for instance. These differences in platforms lead to incompatibilities which tend to separate engineering teams and make it hard to optimize a system in a multi-objective fashion.[23]

An interesting fact is that numerous applications are able to integrate the data of diverse FEM software to conduct the optimization, such as *ModeFrontier* (refer to section *3.2.3*). However, due to the isolation of the engineering teams handling these virtual technologies, the data is not structured in such a way that can be integrated by the software. Here "structured" means a clear view of not only the design variables that affect a single system, but also those that are shared by various systems (i.e., the interactions among systems). This information structuring is one of the challenges to conducting an efficient optimization of the design, even when FEM tools are available.

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[23] It is true that some companies have developed multi-physics applications, such as Comsol Multi-Physics [12], which allow the simulation and evaluation of various functional areas of a system (e.g., acoustics, heat transfer, structural behaviors, etc.), and therefore, the incompatible interfaces are reduced. However, numerous companies, including the O.E.M. under study, still rely in separate applications because, among other reasons, of their ability to handle complex systems in terms of number of finite elements and components.

6. DISCUSSION ON THE ACTUAL ORGANIZATIONAL INTERACTIONS

6.1. General Insights of the Technical and Organizational Ties

By comparing the theoretical and actual networks, three conditions were observed (similar to the findings of Sosa, M. E., *et al* [38]):

A. There is a match in some of the ties present (or not present) in both networks (i.e., the technical product and the organization). This is a beneficial condition for a PDP because information reaches actors with a stake in the design.

B. Some direct ties present in the technical system are not present in the social dimension, meaning that there are intermediaries contributing to the overall connectivity of the network. This condition might not be ideal because intermediaries might filter the information (i.e., act as gatekeepers or bottlenecks) and therefore, critical data might be lost in the process.[5] Also, from the study above, it could mean that there is unawareness about the way the technical systems are actually interrelated. However, it is true that sometimes, especially for non-critical data, intermediaries do permit some teams to get the data much faster.

C. Several ties present in the social dimension are not present in the technical system. Some of these are due to *product ambiguity* in which some interfaces are not foreseen at the initial phases of the project and are discovered once engineering teams work on the product itself.[38] This condition is important to highlight because, while it might represent some redundancies in the interactions;[24] it might also show links that, while not displayed in the

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[24] In some cases, redundancies help to make the design more robust. The redundancies in the internet (e.g., should a server be down, the information can still be retrieved through links with other servers) allows it to continue operating even in the presence of physical disasters.

decomposition of the theoretical system, are actually observed when designing the systems. Therefore, these ties shouldn't be impeded; in fact, it is important to have a mechanism to capture these new interactions because they represent new lessons about the architecture under design (see section *7.1*).

Based on the discussions with engineers, it seems that it is not always necessary to have the organization mimicking 100% the ties of the theoretical system. However, from discussion with PD engineers, it appears to be important that those systems that have a strong relation theoretically, get connected as close as possible through the organization (i.e., with a low number of intermediaries). On the other hand, new interfaces in the product encountered through social interactions, should be recorded for future projects because they represent learning about the architecture. The latter is critical because sometimes, architectural learning (especially in the presence of changes) is hard to achieve.[22]

6.2. Remarks on the Actual Organizational Interactions

From the analysis presented above, there were several organizational conditions that were not favorable for a multi-attribute optimization. These are summarized in the following sections.

6.2.1. Engineering Sites and Cross-Functional Interactions

It is not new that departmental and geographic barriers tend to obstruct communication between teams; numerous works analyzing obstructions to innovation have arrived at this conclusion. Allen, *et al*, 2007 [3] performed a study that showed that the greater the walking distance between two engineers (or scientists), the lower the probability of communication (see *Figure 45*). Nonetheless, what the study presented herein shows that when a particular interaction is cross-functional, this adds still another barrier to the inter-site communication.

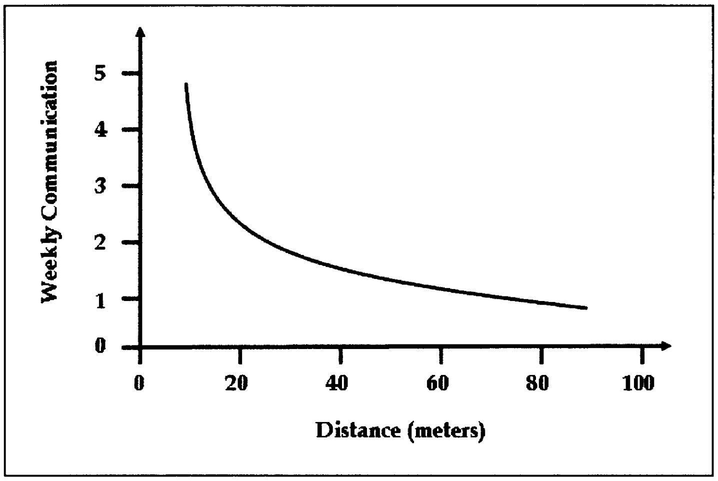

Figure 45. Probability of communication based on distance [3]

As observed, Aero engineers in the US and Germany did show communication ties; however, Energy in NA did not show any direct connection with European engineers in the Aero field, even when they needed information from each other. It was observed that there is a trend of first looking for inter-functional information within the local site rather than in an external location, even when the latter could be a shorter path; in fact, some project leaders encourage this condition. Eventually, the information is retrieved; however, if ways for speeding up the PDP are being investigated, fostering inter-site cross-functional sharing could be an area of opportunity.

None of this is meant to say that site location doesn't affect intra-functional communications. Actually, after conversations with some engineers there is still a preference for working with people not only within the same Engineering site but also within the same building. However, it looks as if inter-functional links are prevented even more because of this condition.

6.2.2. *Lack of a MSDO even under the Presence of Social Interactions*

From the comparison of sociograms it appeared that several of the direct interactions shown by the theory are actually taking place; in other cases, some intermediaries, especially from *Attributes,* did have good level of cross-functional information to link some of the missing ties together. Yet, the organization doesn't show an effective MSDO.

Through some interviews, a couple of factors precluding it were identified: 1) lack of knowledge as to where the different design pieces fit together, and 2) delays in transferring the information to / by overwhelmed intermediaries.

While there is information sharing among some engineers, in most cases they don't have a clear picture of how exactly the information requested actually affects each other's systems. In this sense, the information transfer is done upon request or by what could be called a *pull* process; hence, very little proactive sharing, or *push,* is observed. In other words, if an engineer from team *A* doesn't know that with a design change he or she is affecting the system of team *B*, it can't be expected that *A* will communicate it to *B* unless the latter or any other intermediary asks about it. This obviously delays the process.

Intermediaries such as *Attributes* and D&R engineers do have a better picture of the interactions of the system, at least from a high level perspective; however, in most cases it takes a while for the information to reach them and it is not until this point that cross-team action takes place. In addition to this, due to the numerous interactions inherent in a complex product such as a vehicle, it becomes hard for them to know the effects of all changes. A verbatim quote from an interview with one of the *Attributes* managers exemplifies this: *"The other day an engineer gave me a call indicating that he was planning to add a small bracket in the structure of the vehicle, and that he was expecting that I could tell him all the areas affected from this change… I didn't even now what the bracket looked like and where exactly it was being attached. It is hard for me to know all the engineers that have a stake in a change like this."* There are recurrent meetings or forums intended to have representatives from diverse engineering teams assess the implications of a change. Nevertheless, when the responsibility of some systems is located at external sites (including suppliers) or just because some representatives didn't show up in the forum, the transfer of information starts to become turbulent.

Complementing the discussion above, it is fair to mention that on multiple occasions, the *Attribute,* based on their experience, are able to provide direction in the systems that are affected by a particular change. While experience is a valuable element in engineering leaders, not following robust documentation depicting the interactions between systems could lead to flaws as the number of changes increases. During the interview with the *Attribute* manager mentioned above, he highlighted that it would be desirable to have some mechanism to identify, in a more robust way, how a change can affect other engineering areas.

6.2.3. *Architecture Sensitivity and Complexity of the Information*

There are two more factors that may seem to be influencing the use of intermediaries in the information sharing: sensitivity of the product architecture and the complexity in the information. For the former, in a few cases (for example, between *Aerodynamics* and *Brakes*), it was observed that in the presence of a low sensitivity between the objectives of one team and the design variables handled by other, communication takes place through an intermediary. However, it was also shown that, even though some teams have a significant influence among them (at least from a sensitivity standpoint), communication didn't take place through direct ties. This indicates the presence of some other type of obstacles.

Regarding the complexity of the information, it was observed that the more complex the information, the more social ties become present. Based on some discussions, it was observed that *Weight* didn't have continuous interactions with other engineering groups. The explanation was that, since other teams waited for a particular milestone to update their assumptions, it wasn't until this point when the exchange of information occurred. Besides, the information was limited to the updated weight specifications of the vehicle, and no further data was required. On the other hand, if the information sharing implies different types of data (e.g., drawings, test results, design directions, etc.), then more ties seem to appear.

6.2.4. *Evolution of the Interactions*

Analyzing two phases of the PDP actually showed an evolution in the interactions among a few teams. The reasons for these transitions vary from one team to another, but from the discussions above, two can be highlighted: 1) availability of information, and 2) engineers with switching roles.

- *Availability of information:* Some teams such as Brakes and Wheels/Tires, showed a transition from the first to the second phase based on the availability of information. In particular for Wheels/Tires, early in the process they work with a set of times to get some specifications (vehicle weight, for example) that will be required for the design of the tires. This information is transferred to the suppliers to construct the components. However, once prototypes are available, the interaction occurs with teams actually testing the vehicles.

- *Engineers with switching roles:* In previous discussions it was mentioned that the *Weight* engineer presented the advantage, at least from the standpoint of some engineers, of being the single point of contact for mass-related data. In addition, this engineer was part of the team for most of the duration of the project. Unfortunately, this was not the case with other teams, and in some cases it was not clear who was accountable for specific tasks. Also, it was observed that since managers had to distribute their limited resources as much as possible to maximize their utilization, when the workload in a project was low, engineers were temporarily relocated. These conditions were observed during the first phase in the *Energy* and NA *Aero* engineers interactions, in which the latter were intermittently contributing in the project and on several occasions, there was confusion on who owned a particular responsibility. It wasn't until the end that the *Aero* engineer became more engaged with the project, but the flexibility for change was very limited (not an ideal condition for an effective MSDO).

6.2.5. *Cultural Roadblocks for Timely Information Sharing*

In one of the discussions with the *Energy* team, the idea arose that sometimes changes in the design are not communicated fast enough, driving delays in the deliverables of teams affected by them. When talking with other engineering teams, this behavior seemed to be a *leitmotif*. Obviously, this impedes the *early learning* process described in *Chapter 1*.

According to subsequent interviews with PD managers and engineers, when a significant change in the design assumptions is needed (e.g., addition of a new component, use of a different technology, styling changes in carry-over components, etc.), engineers expect to encounter a lot of resistance from other functional groups. While some proactive engineers might get involved quickly enough to evaluate and support the change, in numerous cases opposing actors request a considerable amount of data before taking a single action. In fact, there are situations in which the data that is being requested would not be available until the last phases of the project, where design changes are extremely expensive (e.g., physical prototypes may not be available and yet, data from actual physical tests rather than the result of CAE analyses are demanded). In other scenarios, the change might be reviewed in multiple forums and design reviews (not very friendly sometimes), eventually discouraging the motivators to implement it until the presence of an unmet target in later phases of the project. One evident result of this is that activities between teams are performed in series rather than in a parallel mode (e.g., until the evidence is provided, other teams begin to act), and longer development times are then expected.

There are other situations in which a *potential* change is being explored by a team and again, it is only communicated once it becomes official. The reason is that other teams might tend to believe that, because a change evaluation is requested, the probability of getting implemented is high. Therefore, they consider the request to be a final notice rather than a proposal and act accordingly. If by any chance, the proposed design is not needed, and worse than that, a new one is required, the reactions from other teams are not very positive.

Through some interviews, it was observed that the promoters of design changes may also contribute to the negative reaction of the receivers. Sometimes, the information is not transferred clearly: rather than providing the full rationale of the change (e.g., explanations about the physical phenomena, limitations of the virtual models, consequences of not making the changes, etc.), a few engineers limit themselves to specifying what is needed (e.g., final geometry, thickness and/or material) without further discussion (sometimes, this is just done via e-mails or automatic notifications through the IT networks). This leads to the disbelief of the receivers and makes them hesitant to work on it.

This situation limits the possibility of having a smooth flow of the PDP.

6.2.6. *Limited Understanding of Experimentation Tools*

It was emphasized before that there seem to be some complications in the interactions between some CAE and test engineers. What it is interesting is that managers, in view of this situation, have taken efforts to integrate these engineers and use their skills more effectively; these have included relocating them (i.e., having them in the same building closer to each other) and in some cases, having them under the same organization. Unfortunately, as mentioned before, there seem to be some other factors which still need to be addressed, and one of them seems to be that there is a lack of knowledge about each other's tools.

From conversations with some CAE and development engineers,[25] it appears that they **do recognize** the value of both tools. On one hand, computer analysts do agree that in order to have more accuracy in their models, they need input from physical tests; however, when some of them were asked about the details of the tests, they confirmed that their knowledge about the way the instrumentation is performed, its limitations and even how vehicles are mocked up is limited. Consequently, sometimes they fail in providing the sufficient amount of information to prepare and conduct the test in a way that can be helpful to them, or may overestimate the information that can be extracted from them.

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[25] As mentioned in the previous chapter, in the company under study, development engineers are responsible for the physical tests.

On the other hand, some development engineers mentioned that they are not very knowledgeable about the fundamentals of CAE models and very often, they limit themselves to retrieving just the data that is comparable to the physical test, without exploring all the information behind them (e.g., deformed shapes, kinematics of components, etc). Also, they are not able to extract the information that could be useful to CAE engineers to correlate their models. Consequently, the full potential of the tools is not utilized.

It is worth mentioning that this is not the case with all engineering teams, as it occurs with the thermal CAE engineer in our analysis (*CAE Thermal US-04)* who was able to handle both tools. As will be discussed in section *7.7,* this and other enablers may contribute to a better integration of these tools.

7. TOWARD AN ENHANCED PDP: CONCLUSIONS AND RECOMMENDATIONS

As hypothesized, comparing the misalignments between a product's architecture and its organization through the use of social network tools (namely, sociograms and centrality statistics) brought up interesting insights about the elements that obstruct the development of complex systems (subsequent interviews with PD actors, were critical for complementing the various network studies). However, it also led to identify some interesting enablers and communication intermediaries that, in some cases, eased the transfer of data, and therefore, the coordination among teams. It is worth mentioning that the use of the sociograms and their statistics was just a part of the analysis. In addition, interviews with PD actors, conducted to understand the differences observed in the networks, was a critical element during the research process.

Having identified enablers and obstacles in the PD process, this chapter tries to provide some general actions and/or considerations that could be followed to enhance the PDP. It is true that just a single project was analyzed, and therefore it can't be claimed that the findings presented hereby are applicable to all PD teams; more work in this field is still required. However, it was considered that providing some suggestions based on literature review, documented best practices from other industries and interviews with engineers could provide good elements to take into account when designing a PD organization.

7.1. Benefits and Further Applications of the N^2 Diagram

Among others, three obstacles were discussed in previous chapters that limit the MSDO:

1) Lack of knowledge on how different systems interact.
2) Delays in information transference due to the existence of overwhelmed intermediaries.

3) Differences in computer platforms to evaluate diverse functions of a single system.

As described before, it is a lack of structure in the information that contributes to these three issues. Ideally, one way to address them would be by making all the engineers of a PD project, regardless of their area of expertise, aware of all the requirements that need to be met by the product. This would mean, for instance, having the NVH engineer knowledgeable not only of his or her requirements, but also of those pertaining to the energy, thermal, safety and vehicle dynamics areas, to name a few. Unfortunately, given the size and the complexity of today's products, this approach might be naïve: It is already a challenge for engineers to understand the targets they need to achieve for their particular system or attribute; therefore, adding more (and not even related to their area of expertise) would make things extremely thorny.

The N^2 Diagram could be a tool addressing this challenge. By having a product decomposed into its individual systems, it clearly shows not all the variables that are related to a module, but those that interface with several. With this view, engineers should be able to understand the effects their decisions have in other functional areas much earlier. Consequently, they could communicate a change to the teams with a stake much faster.

It is worth mentioning that in order for this tool to function effectively, all engineers responsible for the functionality of a product's system or component should have easy access to the diagram. In addition, team actors with high degree centrality, closeness and betweenness in the theoretical networks could administer it by guaranteeing it is updated with the latest level of information; in fact, they could become the optimization leaders during the design phases.

At P&W, an aircraft engine developer and manufacturer, the staff developed a tool called Component Requirements Document (CRD). With this document, they fostered design optimization by breaking down system-level requirements. The issue they had was that, in some cases, teams adhered so tightly to the stated requirements of the document that they did not interact with teams not included in the document. Unfortunately, new designs typically presented new interfaces not explicitly defined in the CRD, leading to a lack of important ties among social actors.[38] As described in the previous chapter, the PD team analyzed showed some interactions among engineering actors not present in the technical systems. In some circumstances these ties were the result of interfaces not previously identified during the decomposition of the product and they could represent undetected interactions of the product's architecture. Considering this and trying to avoid a condition similar to what happened with P&W, there are two important considerations when using the N^2 diagram:

1) It shouldn't be a *cookbook* and therefore, restricting the organizational ties to only those shown in the diagram could eliminate important information channels. Therefore, new ties must be, not only allowed but fostered to establish new information channels.

2) If new ties are created in the social dimension, it is important to capture them in the diagram. Therefore, the N^2 diagram should be considered a living document and has to be updated as new information becomes available.

It is also important to highlight that aside from the *Attributes* team, component and/or system level engineers should also understand what areas are affected when a design change is proposed since they are the actual owners of the parts. Using some basic Six-Sigma tools (see *Figure 46*), they are able to identify how different systems interface and can therefore provide inputs to the appropriate stakeholders in the presence of a change.[26] Unfortunately, due to excessive workloads, inexperience, or even because suppliers in a different site are handling the design, component engineers may miss to cascade the information to some teams. In this case, the N^2 diagram can work as a redundant tool to those shown in *Figure 46*, making the PD processes more robust (e.g., if component engineers fail to cascade a change, those handling the N^2 diagram might not so).

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[26] Further information about these tools can be found in Six Sigma texts.[39]

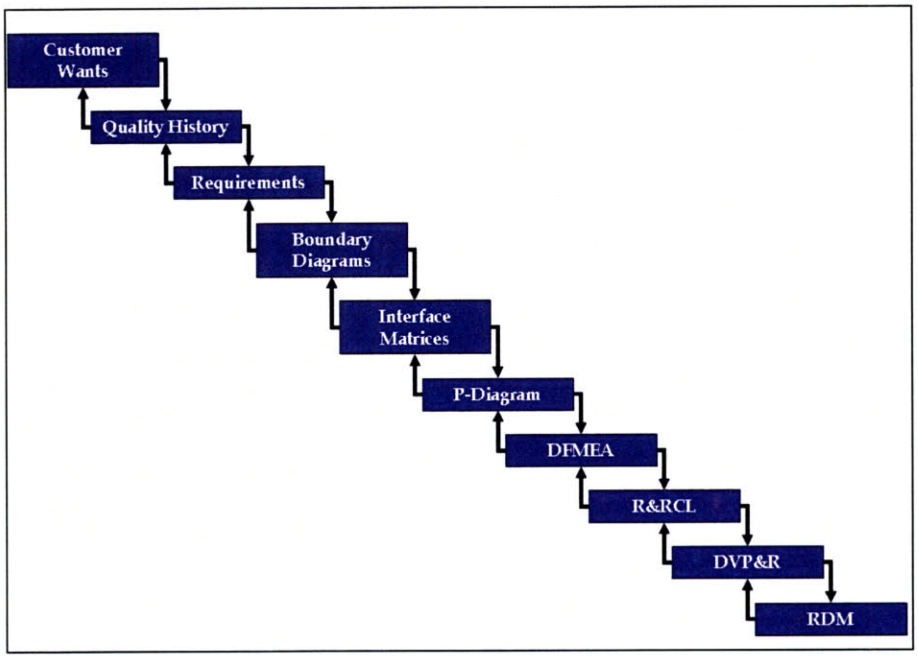

Figure 46. Robustness tools used by component and systems engineers

As highlighted during the review of the social networks, one of the obstacles in cross-functional interactions is that engineers typically don't know the rest of the team working in a product. With discussions with some managers, it was concluded that the construction of the N^2 Diagram could actually be a *team builder* tool. By having representatives of different teams working together in the construction of the diagram during the project's dawn, it could allow them a face-to-face interaction and have them introduced to the co-workers with whom they will be contributing to the endeavor. This initial contact might be the trigger for subsequent informal interactions (e.g., coffee talks, hall discussion, etc.) that have tremendous value for information sharing and innovation in a product development organization.[3]

One last important comment about the use of the N^2 Diagram is the way it should be implemented. Special care must be taken when integrating it into a PD organization. Pushing the tool and forcing engineers to use it without an assimilation process can be dangerous. This could lead not only to their failure to understand its value, but also to its rejection. A critical factor in introducing a new element to an organization is the ability to make evident to its members (or *insiders*[27]) the gaps between the current view of a challenge and its root cause.[25] Through evidence, insiders can realize the true cause of a challenge then become more open to accepting alternative approaches (refer to *Figure 47*). Following this argument, the N^2 diagram should be introduced for the first time in situations where, due to the complexity of the project, it becomes complicated to track all cross-functional interactions. At that point, the diagram could represent a solution and potentially be embraced by team members.

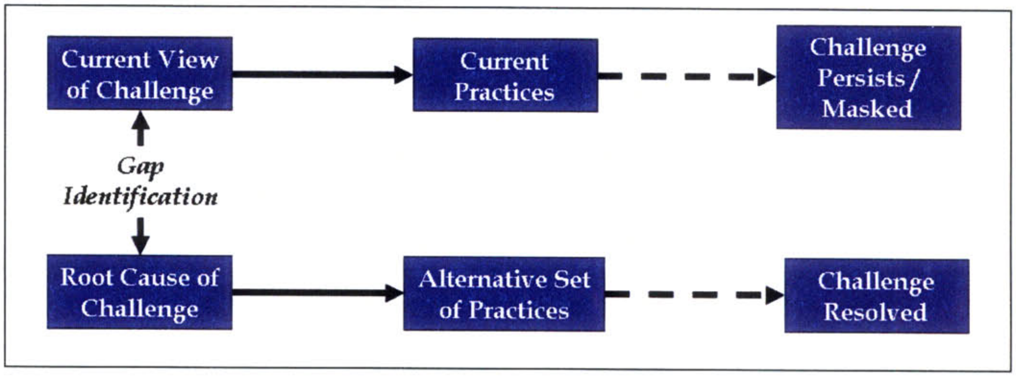

Figure 47. Framework to implement a new tool in an organization [25]

7.2. Organizational Set-ups Based on Diverse Architectures

The N^2 diagram provides a view of the architecture of the system that leads to the construction of the theoretical network. Ideally, it is desired to have the engineering actors linking the modules as prescribed by the N^2 matrix. This would guarantee that the information reaches the appropriate stakeholders. Accordingly, different product architectures would demand different organizational settings.

One of the characteristics of the O.E.M. in the analysis (and which is common to other manufacturers based on discussions with some engineers) is that many engineers are assigned to functional teams (i.e., Functional Organization or Lightweight Project Matrix

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[27] *Insider* is a term that Klein, J. [25] uses to refer to individuals within an organization who are so embedded in its processes that become blind to areas for improvement. On the other hand, *outsiders* are individuals new to the organization that with fresh eyes, are able to highlight areas of opportunity. In words of Klein, "*insiders miss the signals that are often totally apparent to outsiders.*"

Organization [51] in which teams are arranged mostly based on their technical knowledge). Unfortunately, this distribution is very similar across the entire PD organization, regardless of the architecture of the product that is being designed. The *Thermal* organization, for example, is distributed in similar groups in terms of responsibilities,[28] collocated close to each other and each one being accountable for one or two programs depending on their workload. However, depending on the architecture of the product (e.g., distribution of heat shields), Thermal engineers might need to interact closer with different teams. Therefore, it might be worth providing some alignment in the organization based on the given technical architecture (similar to what is called a Project Organization or Heavyweight Project Matrix Organization [51] in which the teams are organized based on the needs of the project itself and not necessarily around their technical expertise).

Unfortunately, there are some cons to organizing PD teams based only on the architecture of the system (for example, the technical expertise may become outdated if engineers reduce their interaction with individuals from the same field [3]). While the author is not pretending to recommend having an organizational set-up based solely on the product, what is being suggested is to at least have some flexibility in the way engineering teams are arranged. Based on interviews, the company in the analysis appears to have some areas of opportunity in this regard, for instance.

7.3. Social Centrality and Physical Centers of Gravity

Allen T., *et al* [3] have performed numerous studies showing how the configuration of a physical space influences the communication among individuals in a company. He even described the concept of *centers of gravity* to refer to the physical spaces in a building that are places where actors of an organization spend most of their time. The argument is that if the time people spend in a given physical space is measured, and then weighted according to the proportion of time, the center of gravity for each individual could be determined. These centers of gravity are influenced by the location of some areas within

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[28] The main difference appears in the size of the group, which depends on the complexity of the project.

the physical space, namely, conference rooms, coffee pots, cafeteria, etc. The idea then is to arrange these sites to influence the movement of the people to achieve the desired interaction.

With the social network statistics presented in previous chapters (i.e., degree centrality, closeness and betweenness), it was possible to determine the actors that were central in the organization. In the project under analysis, some of the most central actors occupied this position mostly because of their roles and responsibilities rather than their physical location. An example was *Attr US-01-02* who as a central actor in the organization even though he was not precisely in a central location of the building. Keeping in mind the concept of *center of gravity*, actors with the greatest amount of ties could also be used to influence them. Accordingly, central engineers could act as the "coffee pots" and "cafeterias" mentioned above. For example, engineers with low centrality in the actual sociogram, but with high *theoretical* centrality could be placed next to central actors to foster their communication with other teams.

It would be helpful to perform social network studies in more projects to create a history of both, the engineering teams that tend to have central roles in the PDP and those that on the contrary, tend to stay isolated. This could provide insights about an adequate distribution of the personnel across a set of given facilities.

7.4. Speeding up Information Sharing under Changed Assumptions

As was discussed in *Chapter 6*, the organization that was studied doesn't response fast in the presence of changed assumptions. The main argument behind this had to do with the way affected teams react and as it was described in *Chapter 6*, in some circumstances the organization is not precisely prone to accept changes. The mindset of *"I won't give you any* (information) *now because I know I'll have to change it later and I know that I'll take the blame for it,"*[10], is not beneficial for the efficiency of the PDP.

If an enhanced PDP is intended, these communication flaws should be addressed. Clark, K. B.; *et al* [10] described how delayed information sharing takes place in several companies, especially Western producers. Also, the research explains how companies that are able to foster **early communication** seem to solve complex problems faster (e.g., Asian manufacturers). Based on this, a 5-dimension model for Integrated Problem Solving is provided, which may be used as a framework to foster early information sharing or interfacing between teams. *Figure 48* shows a graphic representation of this framework: To the left activities conducted in a serial form due to limited communication are depicted; to the right, activities performed in parallel due to rich, dense and early communication are shown. A description of the model is provided below:[10]

1) Timing of Upstream-Downstream activities: in slow organizations, upstream and downstream processes are conducted sequentially because it is not until one task is concluded that the information is transferred to the next team (similar to the conditions described above). The opposite of this implies high frequency of information sharing among teams which represents a reduction in the lead time for problem solving. One mechanism to achieve this is by providing some basic knowledge to different teams about the challenges that other areas encounter. This could make them more sensitive to the needs of each other and therefore, might be willing to communicate and accept design modifications.

2) Richness of Information Media: Some organizations use technology or technical documentation in excess and on occasion these communication media are not the most effective mechanisms for sharing information. Face-to-face interactions should still be fostered to deal with complex challenges. This provides a way to better explain the purpose of a change, building more credibility in the affected parties.

3) Frequency of Information Transmission: Transferring the information regarding a design change in a *single shot*, i.e., once it has been completely refined, is not a desirable condition. It reduces the time other teams have to react and precludes the flexibility of the design. Providing small, but continuous batches of

information is necessary. But to achieve this, engineering actors must understand that changes have the purpose of improving the product. Therefore, the organization, starting from its upper levels, should be more open to them, especially in the initial phases of the project. This would also allow the promoters of design changes to feel more confident that they won't be blamed for them.

4) Direction of Communication: Just as the engineer driving the change should be listened to, he or she must also be open to receiving feedback from the affected actors. It should be understood that, for a proposal, alternative paths can be found that can work for several stakeholders. Therefore, the promoters of change should provide detailed information regarding the rationale, purpose and limitations of the change (not only the final design intent) so that other teams can contribute to an integrated solution more effectively.

5) Timing of Upstream-Downstream Information Flows: Rather than having all stakeholders in a new design involved after all assumptions have been defined, it is usually better to involve them earlier so that they can prepare themselves for the work that will come. This could also make them more flexible to respond faster to rapid changes.

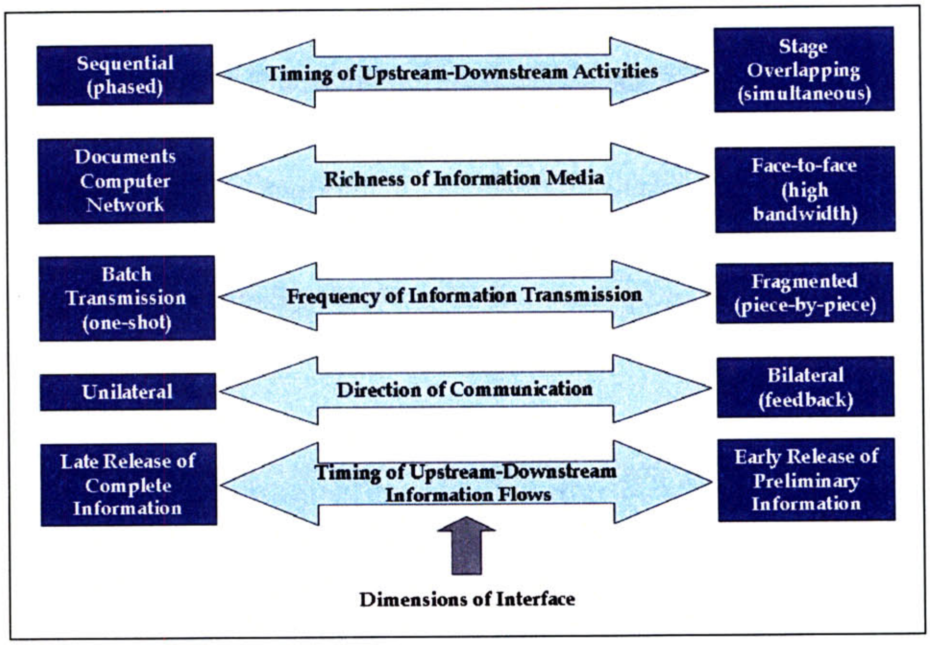

Figure 48. Dimensions of Integrated Problem Solving [10]

The framework presented above could be used to develop further mechanisms to improve team communication in the present of changing assumptions, depending on the characteristics of each particular organization.

7.5. Choosing the Central People for Global Assignments

Along with roles and responsibilities, there are some engineers that have a certain set of social skills that allow them to act as *linchpins* in the development of new products. These individuals are very valuable because they are able to connect teams that would have been disconnected otherwise. These engineers are less affected by social barriers and consequently, can be good enablers for the flow of information.[5]

As was mentioned before, today's PD projects tend to be global. In some instances, this implies the temporal relocation of engineers for several purposes, for example: to federalize or customize a product for a particular market, to share knowledge, to contribute in the presence of insufficient headcount, for training purposes, etc. To determine the actors that will be appointed to these international assignments, several factors are taken into account including technical expertise, ability to adapt to a different culture, willingness of the employee, analytical skills, ability to speak a foreign language and even a subjective perception of its social skills in the local site. Unfortunately, there have been some cases, as described by some managers, that once the engineer arrives at a foreign organization, they significantly reduce contact with their site (even if the contact is needed) and therefore, are not that effective for a GPD project.

A new element that could be taken when choosing individuals for GPD teams could be their centrality in their organization. By conducting surveys, the degree centrality, closeness and betweenness of potential candidates could be determined and therefore, provide a more objective idea regarding how well they are able to link people from different sites. Unfortunately, no social network data was found in the company under study regarding the interactions of engineers prior the described project. Nevertheless, some managers recognize that before the project, *Attr US@E/J-02*, for instance, was a natural *linker* who tended to create ties between various engineering sites over the world. It then makes sense to see that this engineer was very central to the organization, even when he was located in Europe or in Japan.

Assigning engineers with high social network statistics in international assignments could allow the information flow faster and therefore, speed up GPD processes.

7.6. Organizational Clarity

It was mentioned in *Chapter 6* that some teams don't clarify their roles and responsibilities from the beginning of the project. The example was *Aero* team who were confused about the accountability of some tasks, and this also confused the rest of the teams. The opposite of this occurred with the *Weight* engineer who was the only member of this attribute, so it was clear for other teams whom to contact when they needed any mass-related data. Besides, he was part of the team for most of the duration of the project.

Several works support the idea that, an unclear definition of roles and responsibilities or not even knowing who is still working on a project, are certainly factors of confusion in a PD organization.[4] With a GPD project, it becomes critical to achieve organizational clarity because tracking information becomes even more challenging if engineers are dispersed (face-to-face interaction is not possible, for instance). Besides, cultural differences may also create different communication patterns.[1]

It is worth mentioning that organizational clarity doesn't necessarily mean establishing a single point of contact for any cross-functional interaction. While they could be positive to the PDP by acting information brokers (as in the case of the NVH group), there is the risk of having them taking the role of gatekeepers limiting the easy flow of information. All members of an engineering group should show the needed interactions with their counterparts in other teams. The clarity, as mentioned before, is achieved by clearly outlining the roles and responsibilities of each team and making sure these are available to the rest of the actors developing the product.

7.7. Working Cells for Virtual Analysts and Test Engineers

It has already been mentioned on numerous occasions the importance of having an effective integration of virtual and test tools to achieve an effective MSDO, and consequently, enhancing a PDP. The obvious proposal could be having engineers knowledgeable of both, as occurred with the Thermal team in the analysis and a few more attributes in the organization.[29] When engineers have experience conducting CAE analyses and physical tests, they become knowledgeable about the benefits and limitations of each one of them. Consequently, they can use them more effectively to learn much faster about the characteristics of the design and improve it much faster. In fact, the study conducted by Thomke, S. H. [44] shows evidence that companies able to have fewer virtual tools specialists per engineer[30] are more productive and have shorter time to market (see *Table 10*) (for the productivity and time to market comparisons of this study, refer to *Figure 2* and *Figure 3*).

	Use of Tool Specialists		
Important Process Milestones	**US**	**Europe**	**Japan**
Number of CAD specialists per engineer	2.3	0.8	0.3
Percentage of simulation work done by CAE specialists (not design engineers)	75%	36%	37%

Table 10. Use of virtual tool specialists in the global auto industry [44]

Trying to implement the approach above might be feasible with engineers that are new to experimentation tools; i.e., those who are still not biased toward the use of one individual tool. Unfortunately, this is not always the case and in many PD teams test

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[29] While not included in the network analysis, the Safety team also integrates well the computer and test technologies. Many of the Safety engineers conduct both tests and CAE analyses and this makes them knowledgeable about the benefits and limitations of each tool.

[30] Having fewer virtual specialists per engineer implies that other engineers (not only CAE analysts) also make use of them in their tasks.

and computer analysts have been using their respective tools for years and having them switch from one to another might require cultural changes. For example, having a test engineer who has been doing physical vehicle evaluations for years (i.e., manipulating the physical parts, listening to its squeak and rattles, sensing its vibrations, etc.) might find it really hard to start manipulating the vehicle in a 3-D environment where everything becomes purely visual. *"The rate of technological change often exceeds that of behavioral change"* [44], and therefore, virtual technologies are usually manipulated by a group of specialists.

In order to address the complication mentioned above, working cells made up of CAE and test engineers could be helpful. This doesn't mean just locating these two teams next to each other or under the same reporting line. This actually means having them sharing information about the way they conduct their tasks. For example, after conducting a set of simulations, the CAE engineer could share the results with the development engineer, but showing him or her not only plots, as usual, but the deformed shapes, animations, etc. In fact, during the construction of the CAE model (or pre-processing), the virtual analyst could review it with the test engineer to make sure constraints are set-up in a reasonable way, virtual sensors located in the right position, etc. This will provide the test engineer an awareness of how things are set-up in 3-D models (including timings) and potentially, identify some opportunities that could help him or her to conduct tests in such a way as to get more relevant information.

On the other hand, the test engineer should show how physical prototypes are set up. This would include sharing the complexities of prototyping parts, how instrumentation is located, timings to develop the prototype and conduct the test, data that can be extracted, etc. This will help the CAE engineers to build more realistic and helpful models from the standpoint of the development engineers. Finally, having both the awareness of one another's technologies, it should be better for them to discuss and determine the most efficient approaches to conduct a particular evaluation. Also, it will help them share information promptly.

A similar approach was conducted by *Team New Zealand* (TNZ) in the design of a yacht for the 1995 America's Yacht Cup.[24] This team had the challenge to design a world-class yacht with a limited budget. For this, they made use of FEA tools to design the structure of the yacht, as well as CFD programs to simulate the flow of water over its critical surfaces. They also used Velocity Prediction Programs (VPP) to predict the speed of different configurations given a set of wind and sea conditions. Even though the development of the design relied in the intensive use of computer tools, still, many adjustments needed physical evaluations too. They decided that the *"testing of the actual boat in the water would be combined with CFD simulation of the keel."* [24] For this purpose, the people conducting the physical evaluations (i.e., TNZ's crew) were continuously presented with the results of the simulations, including detailed flow-fill graphics. CAE engineers viewed them as their customers and therefore, they made sure the crew understood the performance differences between any two iterations. On the other hand, the crew made sure to provide quick feedback to computer analysts about their findings during the physical evaluations of the boat. These quick cycles driven by a seamless interface among the two teams were an important factor in winning the international yacht competition.

TNZ is a good example on how the improved interactions among experimentation tools could speed up a PDP.

8. FURTHER RESEARCH

All research should lead to more questions. Throughout the previous chapters, methods for comparing the technical systems in organizations have been introduced. Some explanations regarding the differences between the theoretical and actual sociograms were provided based on the analysis of a single PD organization. At the end, some recommendations for enhancing a PDP were provided based on available literature and discussions with PD actors. Yet, there are still many gaps that need to be addressed to enhance a PDP even further.

Aside from the methods and proposals presented in this work, there is a broad variety of research that is being conducted in order to attain an efficient PDP. The purpose of this chapter is not to describe all that research, but to present some further work that could be derived from the studies hereby described.

8.1. Complementing the Present Work

There is further work that can be conducted around the presented research. The first could be the inclusion of other social metrics in the analysis of the networks. Metrics such as *log-linear* p_1 and *logit* p^* as used by Sosa, M. E.; *et al* [38]. In fact, it would be interesting, rather than using the sociograms approach, to construct DSMs and perform a similar approach as Sosa, M. E.; *et al* [38] to see if the results they found in P&W get replicated in an automotive environment. This could provide more data to support or discard the hypothesis presented in that research.

In the present research, just a few systems of the overall product were included. However, another study could include all vehicle systems, and why not different architectures? This would support the conclusion that having a different organization for various architectures might actually be beneficial. This would obviously involve interviewing engineers working on different projects with a different set of requirements to meet.

It would also be worth analyzing in more depth the influence that the relative sensitivity among variables has in the interactions of the organization. Herein, a few systems were analyzed under this parameter and a few trends were identified. And even though there seems to be a trend indicating that, for low sensitivities (i.e., *weak* ties), interactions take place through an intermediary, it would be relevant to perform the analysis for the complete product architecture. This would include calculating the sensitivities with respect to parameters and constraints too.

8.2. Designing a Product Architecture Based on Organizational Interactions

Most of the study for the present work has been focused on identifying and eliminating the obstacles that prevent the social interactions of an organization from mimicking the interdependencies among a product's systems. Under this assumption, the technological system is fixed and the organization must work around this set-up. One can think of several arguments justifying this. For example, it can be stated that a product's pre-established architecture allows the effective (not necessarily efficient) functioning of all systems to achieve the desired tasks.

Nevertheless, another approach can be considered: designing the product's architecture by mimicking the social capital of the team developing it. If we take into consideration that it is hard for a product to be developed or optimized if the right actors don't interact among themselves, this approach may not sound that odd. In fact, it looks as if a few companies have designed the architecture of their products giving an important weight to the individuals who will work on them. The study by MacCormack, A.; *et al* [27] argues that the UNIX-like operating system, Linux, might have taken into account the geographic distribution of "its" programmers during the definition of its loosely linked internal modules.

Designing the architecture of a product considering solely the organizational factor might not be the most efficient approach either; under this scheme, delivering the intended product's function might not be guaranteed. Most probably the right architecture establishes a balance between the technical and societal elements. At the end of the day, the analysis of complex engineering systems must account for the product and the people behind it. However, further research might explore new methodologies to incorporate the organizational factor of a given company in the conception of a new architecture. In this regard, the usage of some of the methods and tools presented in this work (namely, DSM, the theoretical and the actual networks), could play an important role.

8.3. The Role of Timing and other Actors in a PDP

Throughout the document, the analysis of the societal interactions has been based on a set of decomposed technological systems. Hence, most of the central actors analyzed played a technical role around those systems. Nevertheless, there were numerous PD teams that were not included in the analysis, and therefore not all of the overall interactions of the whole PD team were captured. In addition, there were other actors who, without being directly involved in the technical development of systems and components, are critical for the completion of the project. These teams include Marketing, Purchasing, Finance, Sales, among others.

A deeper study of a PD team should include the interactions among the various individuals contributing to a project, technical or non-technical. However, if a similar approach to that presented in previous chapters is used (i.e., decomposing a technical system, constructing the theoretical network and comparing it with actual networks), one of the challenges would be to define the theoretical set-up to which the actual interactions can be compared. The technical decomposition of the systems might not be appropriate for this task as it wouldn't show variables unrelated to the physics of the product (e.g., the construction of the theoretical network of the Marketing team may not be achieved by solely decomposing the product in technical modules). This would imply having different theoretical frameworks for each team; should this be the case, then it might be necessary to find ways to link them altogether (linking the theoretical networks of the PD and Marketing teams, for instance). More research and discussion might be required to address this topic.

Also, in the study, just two design phases grouping several milestones were considered. However, further research should also include more detailed tracking of the teams' interactions at each milestone. This could permit one to see if the expected communication prior each milestone is taking place; otherwise, redesigning the PDP to account not only for the technical but also the organizational elements of the company could be an option.

8.4. Knowledge vs. Enabled Interactions

It was mentioned before that having dispersed engineering teams tends to impede interactions. Therefore, it might be convenient to have engineers in need of high interaction, at least from the point of view of the technical architecture, in a single site. There's one caveat, though, that might be worth considering: most of the time, bringing the right knowledge to a single location might not be possible, as is the case with suppliers, some technical experts, etc. Then the question becomes whether to sacrifice knowledge for enhanced communication or maintain it at the risk of losing critical ties among team members. Understanding how to analyze this tradeoff might provide some considerations to be taken into account when deciding how to distribute the responsibilities of a global product development team.

8.5. Actual Implementation of the Present Work

The ultimate purpose of the present work is to provide some improvement in a PDP. As mentioned before, the conclusions and recommendations described above were based on academic literature, documented cases from companies and discussions with PD managers and engineers.[47] However, a very important next step should be to implement the methods, tools and recommendations in a PD team. So far, a set of observations were presented; from them, some hypothetical recommendations were outlined. Now, it is time to go to the third step: the experimentation. It is critical to test the suggestions and conclusions provided in *Chapter 7* and see if they provide the intended benefits.

A recently formed and growing PD organization might be a good candidate to implement the outlined ideas. By having less *cultural momentum,* it might be more flexible to new behavior, and therefore, new approaches can be tested much faster and more easily (recall the importance of the *early learning*). It might happen that some proposals don't show the intended results and consequently, would have to be revisited. On the other hand, some of them might happen to be successful; however, it is only by actual experimentation that this work might actually provide some value in the PD field.

9. APPENDIX

9.1. Mathematical Description of Objectives

The following bullets describe the targets and objectives used in the analysis (it will be noticed that the objective is basically the target substracted from the calculated value):

1. Maximum Vehicle Speed refers to the highest speed that a vehicle can achieve under a set of conditions specified by the manufacturer's internal test procedures.[31] In the manufacturer's organization this target is the responsibility of the Energy Management engineers.[32] The objective is then defined as follows:

$$\textit{Speed Factor} = SF = \textit{Vehicle's Maximum Calculated Speed} - \textit{Vehicle's Maximum Desired Speed}$$

or

$$SF = Vman - Vmax \qquad \textbf{Equation 11}$$

Ideally a customer would prefer to have a vehicle able to achieve higher speeds, *ceteris paribus*. Therefore, *SF* must be **maximized**: a value greater than *0* means that the target was overachieved, equal to *0* means that the target has been achieved and less than *0* means it has been underachieved. It must be warned that being able to exceed the target speed doesn't necessarily mean that the vehicle will be sold with this overachievement; for safety reasons and other

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[31] The manufacturer's internal test procedures specify the conditions at which each particular objective is evaluated, including but not limited to: ambient conditions, road conditions, altitude, vehicle weight, engine loads, etc.

[32] Being responsible for an objective doesn't mean that a given engineering team must achieve the targets on its own; however, they need to make sure the proper teams are taking the needed actions to deliver it.

technical implications, the maximum speed might be limited through the internal code of the Powertrain Control Module (PCM) should this be the case.

2. Maximum Vehicle Acceleration: for this case, it is the maximum acceleration that a vehicle can achieve from a standing start given a set of conditions specified by the manufacturer's internal test procedures. The objective is the responsibility of the Energy Management engineers an is expressed as:

Performance Factor = PF =
Vehicle's Maximum Calculated Acceleration -
Vehicle's Maximum Desired Acceleration

or

$$PF = a\_fwd\_manual - a \qquad \textbf{Equation 12}$$

It is assumed in this case that a higher achieved acceleration, *ceteris paribus,* is positive for the customer and consequently the higher PF, the better from a customer standpoint. The PF then must be **maximized**: a PF greater than 0 implies an overachieved target; equal means an achieved target and less than 0 means it was underachieved.

3. Maximum Vehicle Gradability refers to the maximum slope that a vehicle can travel at a constant speed under a set of conditions specified by the manufacturer's internal test procedures. The target is the responsibility of the Energy Management engineers and the corresponding objective is defined as:

Grade Factor = GF =
Vehicle's Maximum Calculated Gradability - Vehicle's Maximum Desired Gradability

or

$GF = Gmax\_fwd\_man - Grade$ **Equation 13**

As with the two objectives mentioned before, a customer expects the vehicle to be capable of traveling steep roads and therefore, maximizing this factor is preferred. GF greater than 0 means an overachieved target, equal means achieved, and lower than 0 means that it was underachieved.

4. Maximum Braking Distance (a.k.a. Brake Stopping Distance): this is the distance it takes for the car to reach a complete stop from an initial velocity. The Brake engineers are responsible for delivering the objective, which is expressed as:

$$\textit{Braking Distance Factor} = BF =$$
$$\textit{Vehicle's Maximum Calculated Braking Distance} -$$
$$\textit{Vehicle's Maximum Desired Braking Distance}$$

or

$BF = Stot - S_b$ **Equation 14**

When driving a vehicle there are some circumstances where the customer expects it to stop as fast as possible, especially in emergency situations (e.g., when preventing a car accident). In fact, some countries have regulations limiting the maximum braking distance of a motor vehicle. For instance, the Department of Transportation of the US National Highway Traffic Safety Administration (NHTSA) specifies in its Federal Motor Vehicle Safety Standard (FMVSS) 135 Section 7.5.3 [35] to determine the cold effectiveness of a vehicle's braking system, the stopping distance S for an initial speed V should be less or equal to $0.10V+0.0060V^2$ (with S in meters and V in km/h) under a specific set of test conditions [35]. Based on this, the lower the S_{tot}, the better for the customer and consequently, BF must be **minimized**[33]. Contrasting with the previous factors, a factor greater than *0* means and underachieved target, equal to *0* means achieved, and lower means an overachieved objective.

5. Directional Stability is the ability that a road vehicle has to stabilize its direction of motion in the presence of external disturbances; in other words, after a disturbance it should be able to return to a steady state in a given time. Wong, 2001 [57] indicated that directional stability in a car is achieved if the following simplified expression is satisfied:

$$L + \frac{Vs^2}{g} K_{us} > 0$$ **Equation 15**

where L is the vehicle's wheelbase, Vs is the vehicle's speed for evaluating the steering performance as defined by the manufacturer's verification methods, g is the Earth's gravity (refer to the *Definition of Parameters* section) and K_{us} is the understeer coefficient (refer to the *Steering* submodule). The objective, as expressed below, is the responsibility of the Vehicle Dynamics engineers:

Directional Stability Factor = DS =

Vehicle's Calculated Directional Stability - Vehicle's Desired Directional Stability

or

DS =direc_stab - des_direc_stab **Equation 16**

Good vehicle handling occurs when the directional stability is greater than *0*, and therefore, the directional stability factor should be **maximized** [57]: greater

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[33] From discussions with engineers working in the vehicle project, automotive manufacturers try to exceed the regulatory requirements for several reasons, including but not limited to the competitiveness of the market or as a safety factor. In this particular case, S_b represented 30% less braking distance than what is specified in the FMVSS 135. Therefore, not achieving the target doesn't mean the vehicle can't be sold.

than *0*, equal to *0* or lower than *0* implies overachieved, achieved and underachieved targets, respectively.

6. Ride Quality is the ability of the vehicle to control the vibration so that the occupant's discomfort does not exceed a certain level. One of the methods to address this is by decoupling the interactions between the front and rear suspensions in such a way that the input to the front end doesn't provoke any motion in the rear and vice versa. According to Wong, 2001 [57], one way to achieve this is by adjusting the location of the oscillation centers. These centers are the points at which a road input into the wheels causes a moment; by placing them at the attachment between the vehicle body and front and rear suspension springs, respectively, the interactions get decoupled (refer to the *Handling* submodule for the calculation of the oscillation centers). This condition occurs if the following expression is satisfied:

$$r_y{}^2 = l_1 l_2 \qquad \text{or} \qquad 1 = \frac{r_y{}^2}{l_1 l_2}$$

Equation 17

where r_y is the vehicle's radius of gyration (refer to the *Definition of Parameters* section for a definition of this term), l_1 is the center of gravity of the car with respect to the front axle and l_2 is the center of gravity of the car with respect to the rear axle (while this is a simplification of the vehicle's ride quality estimation, commercial CAE applications such as *ADAMS* [20] as well as physical tests are used to estimate it with a greater level of detail, taking into account more variables).

The equation above represents the ratio of the radius of gyration and oscillation centers for ride quality and for the purpose of the analysis will be referred to as the *Vehicle's Ride Ratio*. The objective, which is handled by the Road NVH engineers, is expressed as:

Ride Ratio Factor = RF =

Vehicle's Calculated Ride Ratio – Vehicle's Desired Ride Ratio

or

$$RF = calc\_ride\_ratio - des\_ride\_ratio \qquad \textbf{Equation 18}$$

This ratio is usually above *1.2* for front-wheel-drive cars [57]; therefore, given the vehicle under study, the *RF* should be **minimized**: a value closer to *0* will provide a good ride condition.

7. Drawbar load capacity, according to the manufacturer, is the amount of load that the vehicle should be able to pull using a towing hitch. This is the responsibility of the Energy Management engineers and the objective can be expressed as follows:

Drawbar Load Factor = DLF =

Vehicle's Calculated Drawbar Load – Vehicle's Desired Drawbar Load

or

$$DLF = Rda - Rd \qquad \textbf{Equation 19}$$

Contrasted to a truck, a small sedan like the one under study is not expected to be able to pull a significant load; however, a certain amount would be desired. Hence, *DFL* should be maximized: a value close to *0* would provide a good competitive advantage to the car.

Finally, the equation used to calculate the global objective is introduced below. It shows the respective weight factors for each partial objective based on the priorities of the vehicle:

$$Global\ Objective=(0.1SF^2+0.15PF^2+0.25GF^2+0.25BD^2+0.15DS^2+0.05RF^2+0.05DLF^2)^{1/2}$$

Equation 20

9.2. Detailed Description of Design Variables

These are defined below:

1. Height of the point of application of the aerodynamic resistance (***ha***): This is an imaginary location at which a concentrated force equivalent to the total aerodynamic drag (***Ra***) generates the same moment in the vehicle as the latter (refer to the *Aerodynamics* submodule). This can be influenced by making some minor changes in the vehicle's front end; this value can only oscillate between *0.92* to *0.97 m* (since most of the exterior components must be kept carry-over, this can't change significantly).

2. Drawbar hitch location (***hd***): Even though several parts of the design are frozen, there is some flexibility to modify the design of the drawbar hitch to place it at different heights with a difference of almost *40 mm* (*0.551* to *0.590 m*).

3. Vehicle's center of gravity along the vertical axis (***h***): Some of the ways this parameter is influenced include the location of the center of gravity of the seats, addition of sheet metal reinforcements at different areas of the structure, volume of the fuel tank, etc.[34] In order to maintain a good rollover stability, ***h*** can oscillate between *0.910* to *1.020 m*.

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[34] A more detailed analysis would include these factors as part of the optimization process; however, it was deemed that the level of detail of the present analysis was adequate to highlight the differences between the systems' interrelationships and the organizational interactions.

4. Vehicle center of gravity along the longitudinal axis with respect to the front axle (***l1***): as before, this parameter can be influenced by the location of the center of gravity of the seats, addition of sheet metal reinforcements at different areas of the structure, volume of the fuel tank, etc. Due to the car's structural design, this variable can go from *0.95* to *1.50 m*.

5. Vehicle weight (***W***): Several components and systems could be modified to influence this design variable, e.g., seat design, fuel tank, body structure, instrument panel, etc. It is estimated that this variable can go from *11,600* to *13,300 N*.

6. Front end characteristic area (***Af***): This is the projected area of the car in the direction of travel [57], as shown in *Figure 49*, which is used to calculate the drag force (refer to the *Aerodynamics* submodule). This can be influenced by a limited amount of modifications in the front end of the car, leading to a range of *1.8* to *2.0* m^2.

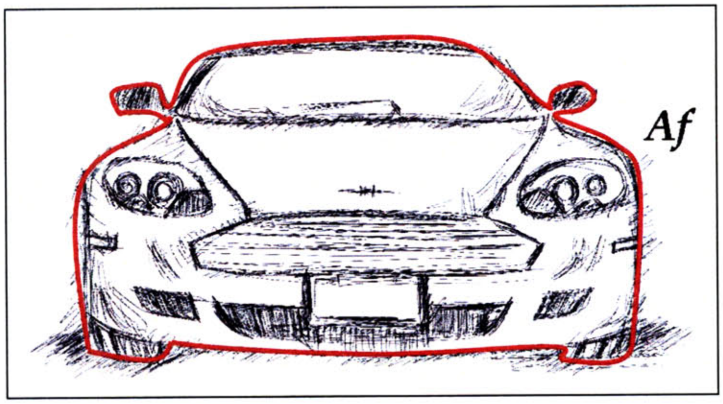

Figure 49. Characteristic area of a vehicle (delimited by the surrounding line)

7. Drag Coefficient (***Cd***): This represents the combined effects of the pressure drag and the skin friction generated by the air in the exterior of the car[35]. It can be

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[35] The pressure drag is the result of the normal pressure on the body; the skin friction is the result of the shear stress in the boundary layer at the car's surface.

influenced by some minor styling modifications (e.g., front end openings). It is expected that in the best case the drag coefficient can change from *0.42* to *0.44*.

8. Rolling radius of the tires (***rtires***): This corresponds to the radius of the tire under operation. While in this case, some constraints (e.g., packaging-wise) don't allow major changes in the radius of the wheels; this variable can be influenced by the stiffness of the tire itself. Depending on the availability of suppliers, this stiffness can change by *1 cm* (from *0.35* to *0.36 m*).

9. Gear ratio in the drive axle (***Eax***): This is basically the final drive which provides additional gear reduction with the consequent torque increase [17]. In the project, there is still some potential to modify it as long as it meets some packaging constraints (based on previous packaging studies, the ratio can be changed from *3.6* up to *3.8*).

10. Cornering stiffness of the front tires (***Caf***): This can be understood as the extent to which the lateral force in the tires changes as the slip angle (formed by the direction of the wheel travel and the line of intersection of the wheel plane with the road) increases [6]. This is influenced by the type of tire selected, which depending on the suppliers, can change from *14,000 N/ra*d to approximately *32,400 N/rad*.

11. Cornering stiffness of the rear tires (***Car***): similar to ***Caf***.

12. Spring stiffness of the front suspension (***kf***): The project still allows for some flexibility to change the stiffness of the suspension springs based on the needs of the NA market. Depending on the coil, material, supplier, etc. the stiffness can oscillate between *60,000* and *75,000 N/m*.

13. Spring stiffness of the rear suspension (***kr***): similar to ***kf***.

14. Actual Drawbar load (***Rda***): this is the calculated load that the vehicle is able to pull using a towing hitch. While it is not mandatory to have a drawbar load capacity, having some would result in a competitive advantage; therefore, it can oscillate between *0* to *1,000 N*.

9.3. Detailed Description of Parameters

a. Vehicle's Physical dimensions:

   i. Vehicle's wheelbase (*L*): distance between the front and rear axles [6]. In the vehicle under study, it is equal to *2.46 m* (see *Figure 53*).

   ii. Vehicle's radius of gyration (*ry*): is defined as the location at which the mass of a body (in this case, the car) can be concentrated without changing the moments of inertia with respect to the coordinate axes [40]. In the car, *ry* was assumed to be *1.33 m*.

b. Components and/or systems specifications:

   i. Steering Gear Ratio (*ES*): equal to *25:1* is the total gear reduction provided by the gears inside the steering box of a rack-and-pinion steering system [17].

   ii. Vehicle's Turning Radius (*Radius*): the radius of a circular turn that the car performs as measured with respect to the car's center of gravity under a set of test conditions as indicated by the manufacturer [57]. In this case, it is specified to be of *20 m* under a specific test condition (see *Figure 50*).

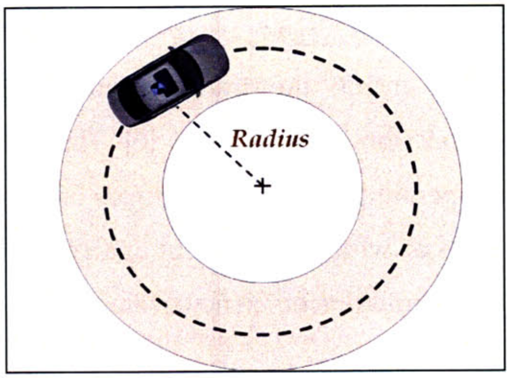

Figure 50. Vehicle's turning radius [30]

iii. Engine Torque (*Me*): For the purpose of the analysis, this was equal to *150 Nm* which was around *94%* of the maximum engine torque and was used to determine the vehicle's tractive effort (refer to the *Transmission* submodule).[36]

iv. Maximum Engine Torque (*Memax*): This is the maximum torque that the engine can provide as specified by the Powertrain engineers and which is equal to *160 Nm* for the present analysis.

v. Engine Speed @ maximum vehicle speed (*ne*): This is typically around *10%* of the maximum engine power, and it is estimated to be around *600 rad/sec* (*5730 rpm*). J.Y. Wong, 2001 [57] explains that having this speed slightly higher than that of the maximum engine power guarantees that enough power would be available to maintain the desired speed under external forces (e.g. wind, grade) or against the deterioration of the engine after extended use.

vi. Engine Speed @ maximum engine power (*ne1*): From the Power vs. Engine Speed curves, it was estimated to be of *545 rad/sec* (*5200 rpm*).

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[36] Typically, an engine produces different torques depending on the rotational speed of the crankshaft and other factors [17]; to simplify the analysis, just two critical values of torque will be selected, *Me* and *Memax*.

vii. Transmission Efficiency (nt): Due to mechanical losses (mainly the friction inside the transmission components), the efficiency of a transmission is never 100% [6]. This value may change depending on the operating speeds and torques of the powertrain systems. Given the speeds at which the present analysis is conducted, it is estimated that the transmission efficiency averages *94%*.

viii. Longitudinal Tire Slip (i): The tire (or wheel) slip is a measure of the difference between its rotational speed and the translational velocity of its center.[29] This is generated by the compression of the internal tire's thread elements as they enter the contact patch with the road (see *Figure 51*). This value changes depending on the vehicle's velocity; however it was estimated that the slip at the speeds under analysis was around *4.5%*.[37]

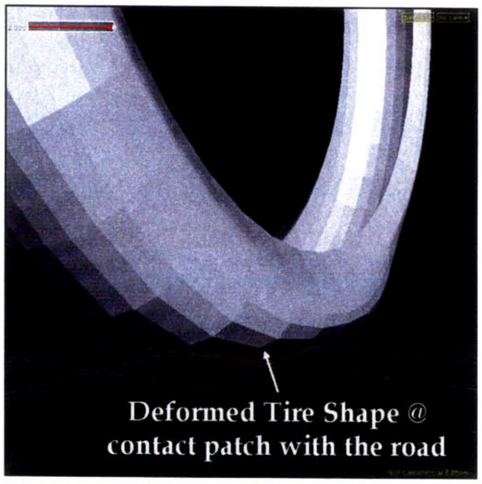

Figure 51. Representation of a deformed tire at the contact with the road [31]

ix. Response time of the brake system (td): Once the brakes are applied, the system shows a time lag before achieving the full braking force. For the

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[37] This factor depends on a number of elements including the type of road surface (sand, rocks, cement, etc.), road conditions (e.g., wet, dry) and tire characteristics (pressure, wear, etc.) among others.[57] Nevertheless, to make the study simpler a single value will be considered; this assumption shouldn't oversimplify the social interactions described in previous chapters.

system used in the present analysis it has been observed to average *0.005 sec.*

x. Slip of the vehicle running gear (*is*): This is the average slip of the gears inside the transmission [57] which is estimated to be of *3.0%* for this case.

xi. Gear ratio factor (*Kg*): This factor is used to estimate the initial gear ratios of the transmission as it represents the average value of the division of two consecutive gear ratios [57]. This is equal to *0.7* and can be expressed as follows:

$$\frac{\frac{E2nd}{E1st}+\frac{E3rd}{E2nd}+\frac{E4th}{E3rd}+\frac{E5th}{E4th}}{4}=Kg \qquad \textbf{Equation 21}$$

c. External physical constants:

  i. Mass Density of the Air (ρ) equal to *1.2* kg/m^3.

  ii. Braking reaction time of driver (*tr*): This is estimated at *0.05 secs* which is the time that it takes for the driver performing the test to apply the brakes.

  iii. Earth's Gravity (g) equal to *9.81* m/sec^2.

d. Test conditions and specifications:

  i. Road Adhesion Coefficient (μ): refers to the friction coefficient between the road and the tire [57]. For a test performed on dry asphalt or concrete, this should be around *0.8*.

  ii. Test Gradability (*Grade_test*): refers to the grade present when performing acceleration tests. While in theory there shouldn't be a slope when performing some of these tests, some grade may actually be present especially when performing evaluations in public roads. Consequently, considering a grade of *2%* in the analysis is recommended by the manufacturer.

iii. Speed of the wind (*Vair*): It is equal to *2.0 m/sec* and is the velocity that the air must have (in the opposite direction to the car's travel) when performing a drag force evaluation under a specific test procedure defined by the manufacturer.

iv. Drawbar load (*Rd*): This is equal to *1,000 N* and is the amount of load that the vehicle should be able to carry under some conditions.

v. Vehicle Speed (*V*): This is the speed used to measure the drag force of the car as well as the rolling resistance of the wheels (refer to the *Aerodynamics* submodule); it is equal to *23.6 m/sec* (*85 km/hr*).

vi. Vehicle Speed prior a braking event (*Vb*): Equal to *22.22 m/sec* (*80 km/hr*), this is the initial speed of the car before bringing it to a complete stop during a braking test.

vii. Vehicle Speed (*Vs*): Equal to *26.4 m/sec* (*95 km/hr*), this is the speed at which the directional stability of the car is tested.

e. Initial targets (refer to the *Definition of Objectives* section):

   i. Desired braking distance (*Sb*): for this case is equal to *32 m* when traveling at the initial velocity *Vb* of *22.22 m/sec (80 km/hr)*. This exceeds the requirement specified in the *Mathematical Description of Objectives* ($Sb \leq 0.10Vb+0.0060Vb^2$).

ii. Desired vehicle acceleration (*a*): Equal to $3.5\ m/sec^2$ given a set of test conditions.

iii. Maximum desired drawbar load (*Rd*): Equal to *1,000 N* given a set of test conditions.

iv. Desired maximum vehicle speed (*Vmax*): this vehicle is expected to achieve a maximum speed of *200 km/hr* ($55.6\ m/sec^2$).

v. Desired ratio of the radius of gyration to the oscillation centers (*des_ride_ratio*): it is desirable to achieve a ratio equal to *1.0*.

vi. Desired directional stability (*des_direc_stab*): it is intended to exceed *0.10 m*.

vii. Desired Gradability (*Grade*): Typically expressed as a percentage, this is the maximum slope that the vehicle should be capable of traveling as defined by $Grade = \tan\theta$ (see *Figure 52*). The target for the vehicle is *30%*.

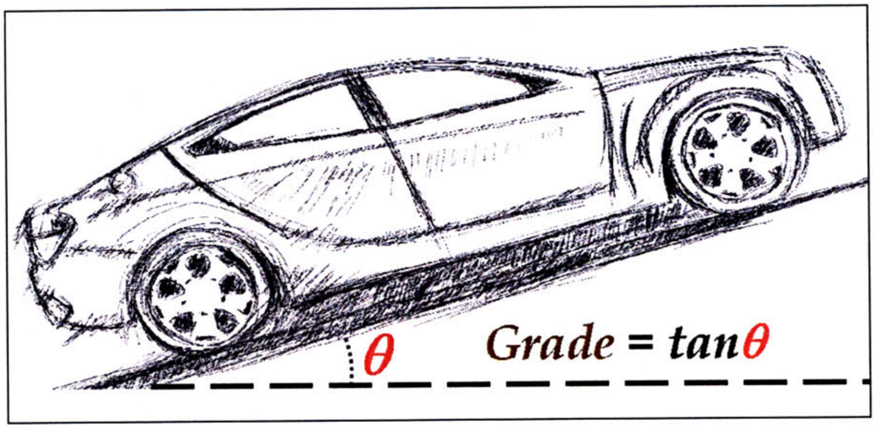

Figure 52. Measurement of a road's grade

9.4. Mathematical Description of Submodules

9.4.1. *Aerodynamics*

Some of the tools used by the manufacturer to perform aerodynamics-related estimations include CFD tools such as *Fluent* and *Star-CD* in the virtual side, as well as wind tunnel and road physical tests. The variables that have been grouped in the *Aerodynamics* submodule are presented next (as mentioned in the *Definition of Objectives,* this arrangement was a function of the engineering teams responsible for estimating them and/or based on the similarities of the tools used):

1. Drag Force (*Ra*): This is the aerodynamic resistance generated by the normal pressure and skin friction originated between the air and moving vehicle when evaluating the vehicle's performance. It is expressed as:

$$Ra = \frac{\rho \cdot Cd \cdot Af \cdot Vr^2}{2}$$ **Equation 22**

where *Vr* is the relative velocity between the air and the vehicle.

2. Drag Force in a braking condition (***Rab***): equivalent to ***Ra*** except that this results when performing a braking test:

$$Ra = \frac{\rho \cdot Cd \cdot Af \cdot Vrb^2}{2}$$ **Equation 23**

where ***Vrb*** is the average relative velocity between the air and the vehicle (for simplification, the vehicle's average speed during the test is considered for the analysis i.e., ***(Vb* + 0)/2**).

3. Speed of the vehicle relative to the wind (*Vr*): This is the difference between the speed of the vehicle and the speed of the air resisting the car's motion. It is expressed as:

$$Vr = V - Vair$$ **Equation 24**

4. Speed of the vehicle relative to the wind in a braking condition (*Vrb*): This is the relative speed between the vehicle and the air at the initial speed of the former prior a braking condition:

$$Vrb = Vb - Vair$$ **Equation 25**

Below, a summary of the variables of the *Aerodynamics* submodule is shown:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Aerodynamics	Ra	1	Drag Force	338.46	N	Aerodynamics	**6,7,9,3**
	Rab	2	Drag Force (braking condition)	302.75	N	Brakes	**6,7,9,4**
	Vr	3	Speed of the vehicle relative to the wind	25.61	m/sec	Aerodynamics	**8,24**
	Vrb	4	Speed of the vehicle relative to the wind (braking condition)	24.22	m/sec	Brakes	**8,25**

Table 11. Summary of the Aerodynamics submodule

9.4.2. *Weight*

Typically, the engineer responsible for tracking the weight of the vehicle uses CAD models, component specifications and spreadsheets to estimate the total weight as well as its distribution in the front and rear axles. Once physical prototypes are available, they are weighted to corroborate the initial estimates.

1. Grade Resistance (*Rg*): This is the component of the vehicle's weight acting normal to the floor as a function of the road's grade:

$$Rg = W \sin\theta$$ **Equation 26**

where θ is the angle of inclination of the road with respect to the horizontal (see *Figure 53*).

2. Load in the front axle (Wf): This is a function of the weight and other forces acting in the vehicle when operating:

$$Wf = \frac{W \cdot l2 \cdot \cos\theta - Ra \cdot ha - \dfrac{h \cdot a \cdot W}{g} - Rd \cdot hd - Rg \cdot h}{L} \qquad \textbf{Equation 27}$$

where $l2$ is the distance between the car's center of gravity and the rear axle, angle of the angle of inclination of the road with respect to the horizontal.

3. Load in the rear axle (Wr): This is a function of the weight and other forces acting in the vehicle when operating:

$$Wr = \frac{W \cdot l1 \cdot \cos\theta + Ra \cdot ha + \dfrac{h \cdot a \cdot W}{g} + Rd \cdot hd + Rg \cdot h}{L} \qquad \textbf{Equation 28}$$

4. Vehicle's center of gravity along the longitudinal axis with respect to the rear axle ($l2$): This is the distance between the center of gravity and the rear axle (refer to *Figure 53*):

$$l2 = L - l1 \qquad \textbf{Equation 29}$$

5. Slope of the road in radians (θ): It is expressed as

$$\theta = a\tan(Grade) \qquad \textbf{Equation 30}$$

Below is the summary of this submodule:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Weight	Rg	1	Grade Resistance	231.95	N	Energy	**5,5**
	Wf	2	Load in the front axle	3357.67	N	Weight	**1,2,3,5,14,3,16,19,1,4,5,1**
	Wr	3	Load in the rear axle	8240.01	N	Weight	**1,2,3,4,5,14,3,16,19,1,5,1**
	l2	4	Center of gravity w.r.t. rear axle	1.129492	m	Weight	**4,3**
	thetha	5	Grade or slope of the road in radians	0.02	radians	Energy	**2**

Table 12. Summary of the Weight submodule

9.4.3. Tires

Non-linear FEM applications such as *LS-Dyna* by Livermore Software Technology Corp. and *Abaqus* by SIMULIA of Dassault Systèmes may be used to perform some analysis on the behavior of the tires; however, they require detailed information about the material properties of the tire's components, which sometimes is not available. Other *motion simulation* software, such as *Adams* by MSC Software, contain some correlated models for describing the behavior of the tires which are used to execute some initial evaluations of the vehicle from a traction standpoint. Physical testing on test tracks is typically the most common tool to evaluate tires performance.

1. Total Rolling Resistance of the tires (*Rr*): This is the force generated mainly due to the deformation processes which occur at the contact patch between the road and the tires (at a lower extent, it can also be influenced by the air circulating inside the tire and the fan effect of the rotating tire) [6] and can be calculated as:

$$Rr = Rrf + Rrr$$ **Equation 31**

2. Rolling Resistance of the front tires (*Rrf*): This is the total rolling resistance of the front tires which is a function of a characteristic rolling resistance coefficient of the tire and the weight it supports.

$$Rrf = frf \cdot Wf \qquad \textbf{Equation 32}$$

3. Rolling Resistance of the rear tires (*Rrr*): This is the total rolling resistance of the rear tires which is a function of a characteristic rolling resistance coefficient of the tire and the weight it supports.

$$Rrr = frr \cdot Wr \qquad \textbf{Equation 33}$$

4. Maximum tractive effort in the front axle (*Fmaxfwd*): This refers to the maximum traction based on the coefficient of friction (or adhesion) between the car's tires and the road and the normal load on the drive axle (since this is a Front Wheel Drive (FWD) vehicle, it refers to the front axle) [57]. It doesn't consider the tractive effort provided by the powertrain. It is estimated as follows:

$$F\max fwd = \mu \cdot Wf \qquad \textbf{Equation 34}$$

5. Maximum slope a FWD vehicle can climb (*grade_max_fwd*): This is based on the coefficient of friction between the road and the tires (i.e., not taking into account the tractive effort provided by the powertrain). It is estimated as:

$$grade\_\max\_fwd = \tan\left(a\sin\left(\frac{F\max fwd - frf \cdot W}{W}\right)\right) \qquad \textbf{Equation 35}$$

6. Rolling resistance coefficient of the front tires (*frf*): This coefficient represents the ratio of the rolling resistance to the normal load in on the front tires. For a vehicle with radial tires (as is the case of the vehicle under study) J. Y. Wong [57] uses as a

reference the models published in Bosch's *Automotive Handbook*, 2nd edition to express the coefficient as a function of the vehicle's speed:

$$frf = 0.0136 + 0.4 \times 10^{-7}(3.6V)^2$$ **Equation 36**

where V is expressed in m/sec.

7. Rolling resistance coefficient of the rear tires (*frr*): As with the coefficient for the front tires, it can be estimated by the equation below:

$$frr = 0.0136 + 0.4 \times 10^{-7}(3.6V)^2$$ **Equation 37**

where V is expressed in m/sec.

Below is the summary of the submodule:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Tires	Rr	1	Total Rolling Resistance	161.08	N	Wheels / Tires	2,3
	Rrf	2	Rolling Resistance of the front tires	46.63	N	Wheels / Tires	2,6
	Rrr	3	Rolling Resistance of the rear tires	114.45	N	Wheels / Tires	3,7
	Fmaxfwd	4	Maximum tractive effort in the front axle (tire & ground)	2686.14	N	Energy	1,2
	grade_max_fwd	5	Maximum slope a FWD vehicle can climb (tire & ground)	22%	%	Energy	5,4,6
	frf	6	Rolling Resistance Coefficient of the front tires	0.014	d.l.	Wheels / Tires	24
	frr	7	Rolling Resistance Coefficient of the rear tires	0.014	d.l.	Wheels / Tires	24

Table 13. Summary of the Tires submodule

9.4.4. *Transmission*

In this analysis, the project is dealing with a manual transmission vehicle and there is flexibility to change the ratios of the gears (usually, with an automatic transmission the determination of the gear ratios is done several years before the vehicle project started). To determine this, there are some applications that run under software such as *Simulink* of *Matlab* by The Mathworks which are used to assess the performance of the transmission at different load and speed conditions. Afterwards, so-called *bench tests* are used to physically analyze the behavior of the transmission at a system level and finally, vehicle level tests are used to evaluate it on actual environments.

1. Gear ratio of the highest gear for a FWD manual transmission vehicle (*E5th*): In this case it refers to the *5th* gear of the transmission, which is typically used to evaluate the maximum speed of the vehicle. To estimate this gear ratio, the equation below can be used [57]:[38]

$$E5th = \frac{ne1 \cdot rtires \cdot (1-i)}{V\max \cdot Eax}$$ **Equation 38**

2. Gear ratio of the lowest gear for a FWD manual transmission vehicle (*E1st*): This gear is used to evaluate the vehicle's gradability and is calculated as follows [57]:

$$E1st = \frac{W \cdot \sin(a\tan(grade\_\max\_fwd)) + frf) \cdot rtires}{Me\max \cdot Eax \cdot nt}$$ **Equation 39**

3. Gear ratio of the second gear (*E2nd*): Using *Kg* this can be estimated:

$$E2nd = E1st \cdot Kg$$ **Equation 40**

4. Gear ratio of the third gear (*E3rd*): similar to *E2nd*:

---

[38] Some minor variations can still occur in the gear ratio due to packaging constraints; however, the calculated ratios are good approximations of the final design.

$$E3rd = E2nd \cdot Kg$$ **Equation 41**

5. Gear ratio of the third gear ($E4th$): similar to $E2nd$ and $E3rd$:

$$E4th = E3rd \cdot Kg$$ **Equation 42**

6. Overall reduction ratio of the transmission at 1st gear (Eo): This includes gear ratio $E1st$ and the reduction provided by the gear ratio in the drive axle:

$$Eo = E1st \cdot Eax$$ **Equation 43**

7. Overall reduction ratio of the transmission at 5th gear (Eo_5th): This includes gear ratio $E5th$ and the reduction provided by the gear ratio in the drive axle:

$$Eo\_5th = E5th \cdot Eax$$ **Equation 44**

8. Vehicle tractive effort ($Fman$): This is the available tractive effort at *1st* gear from a powertrain standpoint. This contrasts with *Fmaxfwd* which is the tractive effort relative to the adhesion between the road and the drive tires. It is calculated as follows [57]:

$$Fman = \frac{Me \cdot Eo \cdot nt}{rtires}$$ **Equation 45**

9. Vehicle speed ($Vman$): It is the maximum speed that the vehicle can achieve based on the overall reduction ratio in the *5th* gear [57]:

$$Vman = \frac{ne \cdot rtires \cdot (1 - is)}{Eo\_5th}$$ **Equation 46**

10. Mass factor (a_m): It refers to a mass factor that takes into account the overall effect of the inertia of the rotating parts (mainly wheels and powertrain components).

J.Y. Wong, 2001 [57] suggests an empirical relation to estimate it based on the overall ratio of the transmission:

For the 1st gear: $$\alpha_m = 1.04 + 0.0025 \cdot Eo^2$$ **Equation 47**

The summary table is shown next:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Transmission	E5th	1	Gear ratio of the highest gear (5th) of a FWD manual vehicle	0.86	d.l.	Powertrain	**8,9,13,15,22**
	E1st	2	Gear ratio of the lowest gear of a FWD manual vehicle	1.64	d.l.	Powertrain	**5,8,9,11,14,5,6**
	E2nd	3	Gear ratio of the second gear of a FWD manual vehicle	1.15	d.l.	Powertrain	**23,2**
	E3rd	4	Gear ratio of the third gear of a FWD manual vehicle	0.81	d.l.	Powertrain	**23,3**
	E4th	5	Gear ratio of the fourth gear of a FWD manual vehicle	0.56	d.l.	Powertrain	**23,4**
	Eo	6	Overall reduction ratio of the transmission (1st gear)	6.25	d.l.	Powertrain	**9,2**
	Eo_5th	7	Overall reduction ratio of the transmission (5th gear)	3.28	d.l.	Powertrain	**9,1**
	Fman	8	Vehicle tractive effort (manual with 1st gear)	2518.25	N	Energy	**8,10,14,6**
	Vman	9	Vehicle speed (manual with 5th gear)	62.17	m/sec	Energy	**8,12,21,7**
	alpha_m	10	Mass factor	1.14	d.l.	Powertrain	**6**

Table 14. Summary of the Transmission submodule

9.4.5. *Performance*

Similar tools to those used for the calculation of the manual transmission parameters are used to deal with the vehicle's performance.

1. Tractive effort available for a FWD manual vehicle (*Favail_fwd_man*): having estimated the available tractive effort from a road-tire and powertrain standpoint, the actual tractive force that the vehicle can provide is equal to the minimum of these two values. For instance, if the powertrain can provide a high tractive effort but the tires begin to slip because of the lack of friction between the road and the tires, it is the latter that defines the maximum tractive effort; on the other hand, if the road adhesion is high but the powertrain cannot generate the sufficient torque to move the vehicle, is the latter that defines the maximum available tractive effort. Therefore, the following expression can be used:

$$Favail\_fwd\_man = \min(F\max fwd, Fman) \quad \textbf{Equation 48}$$

2. Net thrust available for accelerating a FWD manual vehicle (*Fnet_fwd_man*): This represents the longitudinal net force acting in the vehicle which affects its motion. The next figure shows a summary of the main forces acting on the vehicle:

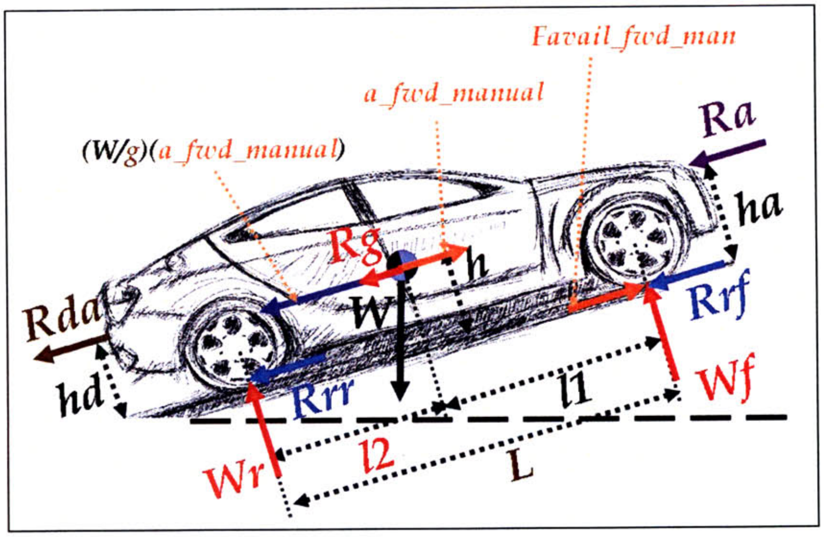

Figure 53. Forces on a vehicle under a longitudinal motion (adapt. from [57])

The net thrust can then be estimated from all the forces previously calculated:

$$Fnet\_fwd\_man = Favail\_fwd\_man - Ra - Rr - Rda - Rg \quad \textbf{Equation 49}$$

3. Acceleration of a FWD manual vehicle (*a_fwd_manual*): with the net thrust and the inertial effects of the rotating parts estimated, Newton's second law is used to estimate the vehicle's acceleration:

$$a\_fwd\_manual = \frac{Fnet\_fwd\_man}{\alpha_m \cdot \dfrac{W}{9.81 m/\sec^2}} \quad \textbf{Equation 50}$$

The following table shows the summary of the module:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Performance	Favail_fwd_man	1	Tractive effort available for a FWD manual vehicle	2518.25	N	Powertrain	4,8
	Fnet_fwd_man	2	Net thrust available for accelerating a FWD manual vehicle	786.76	N	Energy	14,1,1,1,1
	a_fwd_manual	3	Acceleration of a FWD manual vehicle	0.58	m/sec^2	Energy	5,2,10

Table 15. Summary of the Performance submodule

9.4.6. *Gradability*

1. Maximum Grade of a FWD manual vehicle (*Gmax_fwd_man*): This is the maximum grade that a vehicle can travel based on its net thrust and weight:

$$G\max\_fwd\_man = \tan\left(a\sin\left(\frac{Fnet\_fwd\_man}{W}\right)\right)$$ **Equation 51**

Below is the summary table:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Gradability	Gmax_fwd_man	1	Maximum Grade FWD manual vehicle	7%	%	Energy	**5,2**

Table 16. Summary of the Gradability submodule

9.4.7. *Braking*

Non-linear FEM applications such as *LS-Dyna* and *Abaqus* are used by the manufacturer and its suppliers to assess the mechanical performance of the components of a braking system; also, software such as *Fluent* or *Radtherm* from ThermoAnalytics are used to evaluate the behavior of the system from a thermal standpoint. This information can then be integrated to vehicle level CAE analyses in *Adams*, for instance, to understand the overall vehicle behavior. Nevertheless, due to the detailed information about the properties that are used in braking systems (e.g., brake pads), still development tests are required to evaluate and design the appropriate configuration.

1. Proportion of the total braking force on the front axle (*Kbf*): The distribution of the braking forces in the front and rear axles is critical for achieving the maximum braking performance of both axles at the same time (i.e., when none of the tires lock up and therefore there is no slide between the tires and the road). This occurs when the distribution of the braking forces between the front and rear axles is in the same proportion as its respective normal loads and consequently, the maximum braking forces are achieved. *Kbf* can be calculated as [57]:

$$Kbf = 0.95\cdot\left(\frac{l2}{L}+\left(\frac{h}{L}\right)(\mu+frf)\right)$$ **Equation 52**

Kbf is typically controlled by an electronic controller; however, delays in the system as well as other noise factors could preclude the system from working at *100%* at all times. Therefore, a factor of *0.95* is added to the above expression to account for these uncertainties.

2. Proportion of the total braking force on the rear axle (*Kbr*): Based on *Kbf*, it can be estimated as:

$$Kbr = 1 - Kbf \qquad \textbf{Equation 53}$$

3. Deceleration rate of front tires prior lock-up (*decel_rate_f*): With *Kbf* and *Kbr* it can be determined that the deceleration rate in the front tires when they approach lock-up [57]:

$$decel\_rate\_f = \left(\frac{a_{brake}}{g}\right) = \frac{\frac{\mu \cdot l2}{L} + Kbf \cdot frf}{Kbf - \frac{\mu \cdot h}{L}} \qquad \textbf{Equation 54}$$

4. Deceleration rate of front tires prior lock-up (*decel_rate_r*): similar to *decel_rate_f*:

$$decel\_rate\_r = \left(\frac{a_{brake}}{g}\right) = \frac{\frac{\mu \cdot l1}{L} + (1 - Kbf) \cdot frr}{1 - Kbf + \frac{\mu \cdot h}{L}} \qquad \textbf{Equation 55}$$

5. Maximum vehicle's deceleration rate (*decel_rate_max*): This is basically the minimum of both deceleration rates (*decel_rate_f* or *decel_rate_r*) which will determine which tires lock-up first:

$$decel\_rate\_\max = \min(decel\_rate\_f, decel\_rate\_r) \qquad \textbf{Equation 56}$$

6. Braking efficiency (*nb*): It is defined as the ratio of the maximum deceleration rate to the coefficient of road adhesion; it provides an understanding of how much the car uses the available friction coefficient between the tires and the road during a braking condition [57]:

$$nb = \frac{decel\_rate\_\max}{\mu} \qquad \textbf{Equation 57}$$

7. Additional stopping distance (*Sa*): This refers to the travel of the vehicle before the activation of the braking system due to the response time of the brake system and the time it takes for the occupant to apply the brakes:

$$Sa = (td + tr) \cdot Vb \qquad \textbf{Equation 58}$$

8. Total stopping distance (*Stot*): Based on the braking efficiency, additional stopping distance and the forces acting during a braking condition are expressed as [57]:

$$Stot = \frac{W}{2g\left(\frac{\rho}{2} \cdot Cd \cdot Af\right)} \ln\left(1 + \frac{Rab}{\begin{array}{l} nb \cdot \mu \cdot W + \left(\frac{frf + frr}{2}\right) \cdot W \cdot \cos(a\tan(Grade\_test)) + \\ W \cdot \sin(a\tan(Grade\_test)) \end{array}}\right) + Sa$$

Equation 59

This expression assumes that the final speed of the vehicle is *0 m/sec*, which is the case for the test conditions specified by the manufacturer. It also considers the rolling resistance coefficient to be the average between those at the front and rear tires.

Table 17 below shows the summary:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Braking	Kbf	1	Proportion of the total braking force on the front axle	72%	%	Brakes	**3,1,3,4,6**
	Kbr	2	Proportion of the total braking force on the rear axle	28%	%	Brakes	**1**
	decel_rate_f	3	Deceleration rate of front tires (lock-up)	0.89	G	Brakes	**3,1,3,4,6,1**
	decel_rate_r	4	Deceleration rate of rear tires (lock-up)	0.76	G	Brakes	**3,4,1,3,7,1**
	decel_rate_max	5	Maximum vehicle deceleration rate	0.76	G	Brakes	**3,4**
	nb	6	Braking efficiency	95%	%	Brakes	**1,5**
	Sa	7	Additional stopping distance	1.22	M	Brakes	**17,18,25**
	Stot	8	Total stopping distance	37.94	M	Brakes	**5,6,7,1,2,9,19,6,7,2,6,7**

Table 17. Summary of the Braking submodule

9.4.8. *Steering Performance*

In the early stages of an automotive project, different modules of *Adams* to assess the behavior of the steering system at a vehicle level; once physical prototypes are available, they are evaluated under several test conditions on test tracks.

1. Understeer coefficient (*Kus*): This coefficient is used to assess the dependency of the steer angle *df* (see below) on the forward speed of the vehicle. In a car with a *Kus*=0, the steer angle required to negotiate a curve is independent of the forward speed (i.e., neutral steer vehicle); if *Kus*>0, the *df* required increases with the square of the vehicle forward speed (i.e., understeer condition); finally, if *Kus*<0, the required *df* decreases with an increase of forward speed (i.e., oversteer condition) [57]. This coefficient is calculated as:

$$Kus = \frac{Wf}{2 \cdot Caf} - \frac{Wr}{2 \cdot Car}$$ **Equation 60**

2. Steer angle required to negotiate a given curve (*df*): This angle is measured at the wheels (not at the steering wheel):

$$df = \frac{L}{Radius} + Kus \cdot \left(\frac{Vs^2}{g \cdot Radius} \right)$$ **Equation 61**

3. Characteristic or critical speed (*Vsteering*): This is the speed at which the steer angle required in a curve is either *2L/Radius* for the case of an understeer condition (characteristic speed) or *0* for an oversteer vehicle (critical speed) [57]. It is calculated as follows:

$$Vsteering = \sqrt{\frac{g \cdot L}{|Kus|}}$$ **Equation 62**

4. Yaw Velocity (*Ωz*): Yaw refers to the rotation about the vertical axes of a vehicle [57] (refer to *Figure 54* for other rotational motions present in a car).

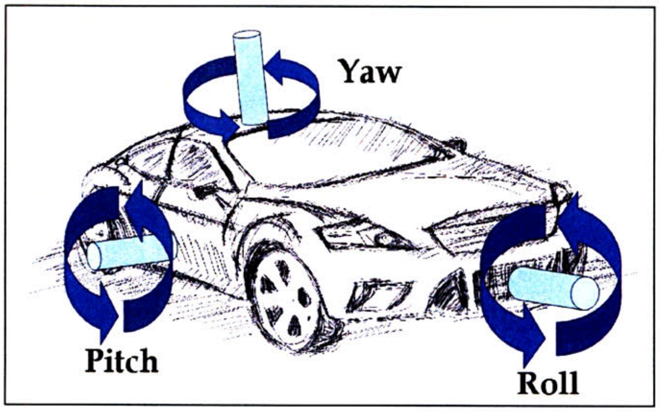

Figure 54. Vehicle's pitch, roll and yaw

Yaw velocity is then, the angular speed of the car around the vertical axis and is calculated as [6]:

$$\Omega z = \frac{Vs}{Radius} \qquad \textbf{Equation 63}$$

5. Yaw Velocity Gain (*Gyaw*): This is a parameter used for comparing the response of the steering system in road vehicles. It is equal to the ratio of the yaw velocity at a steady state to the steer angle [57]:

$$Gyaw = \frac{\Omega z}{df} \qquad \textbf{Equation 64}$$

6. Lateral Acceleration Gain (*Gacc*): This is another output from a vehicle under a turning condition and it is equal to the ratio of the lateral acceleration (at a steady-state) to the steer angle. As it is also used to evaluate the response of the steering system [57]:

$$Gacc = \frac{\frac{Vs^2}{g \cdot Radius}}{df} \qquad \textbf{Equation 65}$$

7. Curvature to the steer angle ratio (*Curv*): It provides the curvature response of the car with respect to the steer angle of the front wheel and is also used to evaluate the steering response of the car. It is calculated as [57]:

$$Curve = \frac{\frac{1}{Radius}}{df} \qquad \textbf{Equation 66}$$

8. Yaw velocity gain with respect to (w.r.t.) the steering wheel angle (*Gyaw_st*): It depends on the steering gear ratio:

$$Gyaw\_st = \frac{Gyaw}{Es}$$ **Equation 67**

9. Lateral acceleration gain w.r.t. the steering wheel angle (*Gacc_st*):

$$Gacc\_st = \frac{Gacc}{Es}$$ **Equation 68**

10. Curvature to the steer angle ratio w.r.t. the steering wheel angle (*Curv_st*):

$$Curv\_st = \frac{Curv}{Es}$$ **Equation 69**

Table 18 shows the summary of the submodule:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Steering Performance	Kus	1	Understeer coefficient	-0.03	d.l.	Steering	**10,11,2,3**
	df	2	Steer angle required to negotiate a given curve	0.00	rad	Steering	**3,6,19,26,1**
	Vsteering	3	Characteristic or critical speed (steering)	26.94	m/sec	Steering	**3,19,1**
	Omegaz	4	Yaw velocity	1.32	rad/seg	Vehicle Dynamics	**6,26**
	Gyaw	5	Yaw velocity gain	263.93	1/seg	Vehicle Dynamics	**2,4**
	Gacc	6	Lateral Acceleration Gain	709.96	d.l.	Vehicle Dynamics	**6,19,26,2**
	Curv	7	Curvature to the steer angle ratio	10.00	1/m	Vehicle Dynamics	**6,2**
	Gyaw_st	8	Yaw velocity gain w.r.t. the steering wheel angle	10.56	1/seg	Vehicle Dynamics	**5,5**
	Gacc_st	9	Lateral Acceleration Gain w.r.t. the steering wheel angle	28.40	d.l.	Vehicle Dynamics	**5,6**
	Curv_st	10	Curvature to the steer angle ratio w.r.t. the steering wheel angle	0.40	1/m	Vehicle Dynamics	**5,7**

Table 18. Summary of the Steering Performance submodule

9.4.9. *Handling*

The engineering team responsible for the handling of the vehicle deals with its response to the commands of the user as well as its stabilization under noise factors. It is closely related, among other systems, to the steering performance previously described. Simulations using *Adams* and road tests are used to evaluate and develop the vehicle design from a handling standpoint. Below a description of some of the parameters measured during development tests.

1. Slope of the steer angle-lateral acceleration curve @ constant radius test (*Rconstant*): It is estimated in a condition where the vehicle is maneuvered on a curve with a constant radius at different speeds. The steer angle required to maintain the course is then plotted w.r.t. the lateral acceleration. Depending on the slope of the curve, it can be determined if the car is under, over or neutral steer [57]:

$$Rcons\tan t = Kus \qquad \textbf{Equation 70}$$

2. Slope of the steer angle-lateral acceleration line @ constant speed test (*Vconstant*): In this case, the vehicle is driven at a constant speed but different curve radii are evaluated. If the vehicle is neutral steer, the slope of the curve will be constant; should it be understeer, the slope will be greater than that of the neutral steer condition; on the other hand, it would be oversteer if the slope is less than that for the neutral steer condition [57]:

$$Vcons\tan t = \frac{g \cdot L}{Vs^2} + Kus \qquad \textbf{Equation 71}$$

3. Slope of the steer angle-lateral acceleration line @ constant steer angle test (*Stconstant*): Similar to the previous cases, under this condition the steer angle is kept constant and the accelerations at various speeds are measured. A neutral steer vehicle will show a slope equal to zero; in an understeer, it will be negative; for an oversteer, the slope will be positive. It is calculated as [57]:

$$Stcons\tan t = -\frac{Kus}{L}$$ **Equation 72**

4. Calculated directional stability (*direc_stab*): This can be determined using the following expression presented by J. Y. Wong [57]:

$$direc\_stab = L + \frac{Vs^2}{g} Kus$$ **Equation 73**

As described in the *Definition of Objectives*, the vehicle is directionally stable if ***direc_stab*** is greater than *0*, which is always the case for an understeer condition (*Kus* > *0*), or when ***Vs*** < ***Vsteering***.

The summary appears in *Table 19*:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Handling	Rconstant	1	Slope of the steer angle-lateral acceleration curve (constant radius test)	-0.03	d.l.	Vehicle Dynamics	**1**
	Vconstant	2	Slope of the steer angle-lateral acceleration line (constant speed test)	0.00	d.l.	Vehicle Dynamics	**3,19,26,1**
	Stconstant	3	Slope of the steer angle-lateral acceleration curve (constant steer angle test)	0.01	1/m	Vehicle Dynamics	**3,1**
	direc_stab	4	Calculated directional stability	0.10	m	Vehicle Dynamics	**3,19,26,1**

Table 19. Summary of the Handling submodule

9.4.10. Ride

There are several tools used by the O.E.M. to evaluate the vibration of the different systems of the vehicle to assess its effects on the occupants. From a structural standpoint, software such as *Nastran* as well as other applications developed internally allow some of these evaluations; also, vehicles instrumented with accelerometers and other devices are used in the development of motor vehicles.

1. First coefficient for bounce and pitch (*D1*): this is one of the coefficients of a two-degree of freedom equation of motion used to model the behavior of a simplified two degrees of freedom vehicle model [57]:[39]

$$D1 = \frac{(kf + kr)}{\frac{W}{g}} \qquad \textbf{Equation 74}$$

2. Second coefficient for bounce and pitch (*D2*): similar to *D1*:

$$D2 = \frac{(kr \cdot l2 - kf \cdot l1)}{\frac{W}{g}} \qquad \textbf{Equation 75}$$

3. Third coefficient for bounce and pitch (*D3*): similar to *D1* and *D2*:

$$D3 = \frac{(kf \cdot l1^2 + kr \cdot l2^2)}{\frac{W}{g} ry^2} \qquad \textbf{Equation 76}$$

With the above coefficients the following equations of motion are constructed:

$$\ddot{z} + D1 \cdot z + D2 \cdot \theta_v = 0 \qquad \textbf{Equation 77}$$

$$\ddot{\theta}_v + D3 \cdot \theta_v + \frac{D2}{ry^2} z = 0 \qquad \textbf{Equation 78}$$

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[39] Two simplify the model, damping effects were ignored.

where z is the linear vertical displacement of the vehicle's center of gravity and θ_z is the angular displacement of the body.

4. First bounce and pitch frequency ($wn1$): Solving the two equations above and making some substitutions, the two undamped natural frequencies of the system can be estimated [57]:

$$wn1 = \sqrt{\frac{1}{2}(D1 + D3) - \sqrt{\frac{1}{4}(D1 - D3)^2 + \frac{D2^2}{ry^2}}}$$

Equation 79

5. Second bounce and pitch frequency ($wn2$): similar to $wn1$:

$$wn2 = \sqrt{\frac{1}{2}(D1 + D3) + \sqrt{\frac{1}{4}(D1 - D3)^2 + \frac{D2^2}{ry^2}}}$$

Equation 80

6. First bounce and pitch frequency ($wn1Hz$): refers to $wn1$ in Hertz:

$$wn1Hz = \frac{wn1}{2\pi}$$

Equation 81

7. Second bounce and pitch frequency ($wn2Hz$): refers to $wn2$ in Hertz:

$$wn2Hz = \frac{wn2}{2\pi}$$

Equation 82

8. Location of the first oscillation center w.r.t. the vehicle's c.g. ($lo1$): As mentioned in the *Definition of Objectives*, an oscillation center is the point at which a road input at the front or rear wheel causes a moment. The oscillation at this center provides information about the vehicle's motion [57]:

$$lo1 = \frac{D2}{wn1^2 - D1}$$ **Equation 83**

9. Location of the first oscillation center w.r.t. the vehicle's c.g. ($lo2$): similar to $lo1$:

$$lo2 = \frac{D2}{wn2^2 - D1}$$ **Equation 84**

10. Calculated ratio of radius of gyration to the oscillation centers for ride ($calc\_ride\_ratio$): This expression allows one to determine whether the oscillation centers are located at the point of attachment of the suspension springs to the body (refer to *Definition of Objectives*):

$$calc\_ride\_ratio = \frac{ry^2}{l1 \cdot l2}$$ **Equation 85**

The summary is shown next:

	Symbol	ID #	Name	Value	Units	Eng. Team	Inputs
Ride	D1	1	First coefficient for bounce and pitch	101.48	sec^(-2)	NVH	9,12,13,19
	D2	2	Second coefficient for bounce and pitch	-10.20	m-sec^(-2)	NVH	4,9,12,13,19,4
	D3	3	Third coefficient for bounce and pitch	87.38	sec^(-2)	NVH	4,9,12,13,7,19,4
	wn1	4	First bounce and pitch frequency	9.17	sec^(-1)	NVH	7,1,2,3
	wn2	5	Second bounce and pitch frequency	10.24	sec^(-1)	NVH	7,1,2,3
	wn1Hz	6	First bounce and pitch frequency in Hertz	1.46	Hz	NVH	7,1,2,3
	wn2Hz	7	Second bounce and pitch frequency in Hertz	1.63	Hz	NVH	7,1,2,3
	lo1	8	Location of first oscillation center w.r.t. the vehicle's cg (x-direction)	0.58	M	NVH	1,2,4
	lo2	9	Location of the first oscillation center w.r.t. the vehicle's cg (x-direction)	-3.03	M	NVH	1,2,5
	calc_ride_ratio	10	Calculated ratio of radius of gyration to the oscillation centers for ride	1.18	d.l.	NVH	4,7,4

Table 20. Summary of the Ride submodule

9.5. Calculation of Relative Sensitivities

In order to compare the sensitivities from different design variables, the calculation of their *relative* sensitivity should take place through a normalization.[14] This is performed using the following expression:

$$\nabla \bar{J} = \frac{x^o}{J(x^o)} \nabla J$$ **Equation 86**

where x^o is the value of the design variable after the optimization, $J(x^o)$ is the value of the optimized objective and ∇J is the gradient of the objective with respect to a given design variable.

In this case, rather than calculating the sensitivity with respect to the global objective, the partial objectives will be taken into account. It is assumed that this will provide a better idea of the sensitivity among a given set of technical systems. It is also worth mentioning that only the sensitivities that will provide insights during the comparative analysis of the social and technical sociograms will be calculated.

The next table shows the relative sensitivity of the *Brake Distance Factor (BD)* which is handled by the *Brakes* team with respect to all the design variables.[40] With this, a reference of the strength of the ties between *Brakes* and those shown in the column *Eng. Team* is provided.

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[40] It is worth mentioning that in all the sensitivity tables presented in this section, a relative sensitivity equal to *0* could also mean that it is numerically insignificant.

	Symbol	**Eng. Team**	**Relative Sensitivity***
Design Variables	ha	Aerodynamics	0.1
	hd	Energy	0.1
	h	Weight	0.1
	l1	Weight	0.6
	W	Weight	0.1
	Af	Studio	0.1
	Cd	Aerodynamics	0.1
	rtires	Wheels / Tires	0.1
	Eax	Powertrain	0
	Caf	Wheels / Tires	0
	Car	Wheels / Tires	0
	kf	Chassis	0
	kr	Chassis	0
	Rda	Energy	0

**The purpose of the sensitivity study is solely to understand the strength among the links; thus, the absolute value is shown*

Table 21. Relative sensitivity of the BD factor w.r.t. the design variables

Table 25 shows the relative sensitivity of the weight at the front and rear axles (*Wf* and *Wr*, respectively), with respect to the design variables. Obviously, the two are handled by the *Weight* team.

	Symbol	Eng. Team	Relative Sensitivity (Wf)*	Relative Sensitivity (Wr)*
Design Variables	ha	Aerodynamics	0	0
	hd	Energy	0.1	0
	h	Weight	0.5	0.2
	l1	Weight	1.9	0.8
	W	Weight	1.1	1
	Af	Studio	0	0
	Cd	Aerodynamics	0	0
	rtires	Wheels / Tires	0	0
	Eax	Powertrain	0	0
	Caf	Wheels / Tires	0	0
	Car	Wheels / Tires	0	0
	kf	Chassis	0	0
	kr	Chassis	0	0
	Rda	Energy	0.1	0

The purpose of the sensitivity study is solely to understand the strength among the links; thus, the absolute value is shown

Table 22. Relative sensitivity of the w.r.t. the design variables

In the following table, the absolute relative sensitivity of the *Speed*, *Performance* and *Grade* factors are shown; the three of them are handled by the *Energy* team.

	Symbol	Eng. Team	Relative Sensitivity (SF)*	Relative Sensitivity (PF)*	Relative Sensitivity (GF)*
Design Variables	ha	Aerodynamics	0	0	0
	hd	Energy	0	0	0
	h	Weight	0	0.3	0.4
	l1	Weight	0	1.2	1.7
	W	Weight	0	0.3	0.6
	Af	Studio	0.6	0.1	0
	Cd	Aerodynamics	0.7	0	0
	rtires	Wheels / Tires	0	0	0
	Eax	Powertrain	0	0	0
	Caf	Wheels / Tires	0	0	0
	Car	Wheels / Tires	0	0	0
	kf	Chassis	0	0	0
	kr	Chassis	0	0	0
	Rda	Energy	0	0.3	0.4

The purpose of the sensitivity study is solely to understand the strength among the links; thus, the absolute value is shown

Table 23. Relative sensitivity of the performance and grade factors w.r.t. the design variables

9.6. Measures of the Theoretical Social Network

Degree Centrality / Theoretical Sociogram						
Engineering Team	**Degree (CD)**	**Relative Degree (CD')**	**Out-Degree**	**Relative OutDegree***	**In-Degree**	**Relative InDegree***
Aero	22	19.8	14	12.6	8	7.2
Architecture	17	15.3	17	15.3	0	0.0
Brakes	59	53.2	16	14.4	43	38.7
Chassis	6	5.4	6	5.4	0	0.0
Energy	69	62.2	35	31.5	34	30.6
NVH	64	57.7	20	18.0	44	39.6
Powertrain	50	45.0	25	22.5	25	22.5
Steering	28	25.2	16	14.4	12	10.8
Studio	3	2.7	3	2.7	0	0.0
Veh Dyn	46	41.4	17	15.3	29	26.1
Weight	67	60.4	41	36.9	26	23.4
Wheels / Tires	27	24.3	19	17.1	8	7.2

** Figures multiplied by 100*

Table 24. Degree centrality of the theoretical social network

Closeness / Theoretical Sociogram		
Engineering Team	**Relative inCloseness***	**Relative outCloseness***
Aero	5.5	7.5
Architecture	1.8	2.6
Brakes	14.5	14.0
Chassis	1.8	1.9
Energy	24	23.9
NVH	11.6	10.9
Powertrain	15.8	14.3
Steering	5.2	4.7
Studio	0.9	1.3
Veh Dyn	16.6	13.8
Weight	6.6	9.8
Wheels / Tires	8.7	8.9

** Figures multiplied by 100*

Table 25. Closeness of the theoretical social network

Betweenness / Theoretical Sociogram		
Engineering Team	**Betweenness (CB)**	**Relative Betweenness (CB')***
Aero	196.5	3.2
Architecture	0	0.0
Brakes	170.5	2.8
Chassis	0	0.0
Energy	657.6	10.8
NVH	50	0.8
Powertrain	452.7	7.4
Steering	441	7.2
Studio	0	0.0
Veh Dyn	113	1.9
Weight	560.5	9.2
Wheels / Tires	140.2	2.3

Figures multiplied by 100

Table 26. Betweenness of the theoretical social network

9.7. Measures of the Actual Social Networks (Phase I and II)

Degree Centrality / Actual Sociogram Phase I						
Engineering Team	**Degree (CD)**	**Relative Degree (CD')***	**Out-Degree**	**Relative Out-Degree***	**In-Degree**	**Relative In-Degree***
Aero	4	1.80	4	1.80	4	1.80
Architecture	9	4.05	8	3.60	8	3.60
Attributes	67	30.18	46	20.72	49	22.07
Body	4	1.80	4	1.80	1	0.45
Body CAE	16	7.21	7	3.15	12	5.41
Body Structure	6	2.70	6	2.70	3	1.35
Brakes	18	8.11	16	7.21	16	7.21
CAD	2	0.90	1	0.45	2	0.90
Chassis	48	21.62	30	13.51	28	12.61
Chassis Supplier	2	0.90	2	0.90	0	0.00
Chief Engineer	23	10.36	21	9.46	19	8.56
Durability	2	0.90	2	0.90	1	0.45
Electrical	21	9.46	16	7.21	15	6.75
Energy	2	0.90	0	0.00	2	0.90
Finance	2	0.90	2	0.90	2	0.90
Integration	17	7.66	12	5.41	10	4.50
Manuf	2	0.90	2	0.90	2	0.90
Marketing	5	2.25	5	2.25	5	2.25
NVH	36	16.21	21	9.46	24	10.81
NVH CAE	1	0.45	1	0.45	0	0.00
PD_Manuf_Liason	1	0.45	1	0.45	1	0.45
Planning	3	1.35	3	1.35	2	0.90
PM	39	17.56	24	10.81	31	13.96
Powertrain	15	6.75	15	6.75	11	4.95
Purchasing	4	1.80	2	0.90	2	0.90
Quality	2	0.90	2	0.90	2	0.90
R&D	4	1.80	2	0.90	2	0.90
Restraint	1	0.45	0	0.00	1	0.45
Safety	4	1.80	2	0.90	2	0.90
Sales	1	0.45	0	0.00	1	0.45
Service	2	0.90	2	0.90	2	0.90
Steering	9	4.05	9	4.05	7	3.15
Studio	1	0.45	1	0.45	1	0.45
Testing	21	9.46	14	6.31	16	7.21
Thermal	19	8.56	13	5.86	14	6.31
Veh Dyn	25	11.26	16	7.21	12	5.40
Weight	9	4.05	8	3.60	5	2.25
Wheels / Tires	11	4.96	4	1.80	9	4.05

Figures multiplied by 100

Table 27. Degree centrality of the actual social network Phase I

Degree Centrality / Actual Sociogram Phase II						
Engineering Team	**Degree (CD)**	**Relative Degree (CD')***	**Out-Degree**	**Relative Out-Degree***	**In-Degree**	**Relative In-Degree***
Aero	7	3.15	6	2.70	7	3.15
Architecture	3	1.35	2	0.90	1	0.45
Attributes	75	33.78	57	25.68	56	25.22
Body	6	2.70	6	2.70	1	0.45
Body CAE	16	7.21	7	3.15	12	5.41
Body Structure	8	3.60	8	3.60	4	1.80
Brakes	10	4.50	10	4.50	6	2.70
CAD	3	1.35	2	0.90	1	0.45
Chassis	40	18.01	26	11.71	21	9.46
Chassis Supplier	2	0.90	2	0.90	0	0.00
Chief Engineer	19	8.56	17	7.66	18	8.11
Durability	5	2.25	4	1.80	4	1.80
Electrical	14	6.30	8	3.60	9	4.05
Energy	6	2.70	3	1.35	5	2.25
Finance	1	0.45	0	0.00	1	0.45
Integration	22	9.91	13	5.86	12	5.40
Manuf	7	3.15	5	2.25	6	2.70
Marketing	4	1.80	4	1.80	4	1.80
NVH	37	16.66	21	9.46	25	11.26
NVH CAE	0	0.00	0	0.00	0	0.00
PD_Manuf_Liason	2	0.90	2	0.90	2	0.90
Planning	3	1.35	2	0.90	3	1.35
PM	33	14.86	22	9.90	25	11.25
Powertrain	30	13.51	27	12.16	22	9.91
Purchasing	1	0.45	1	0.45	1	0.45
Quality	3	1.35	3	1.35	3	1.35
R&D	3	1.35	1	0.45	2	0.90
Restraint	1	0.45	0	0.00	1	0.45
Safety	6	2.70	4	1.80	4	1.80
Sales	0	0.00	0	0.00	0	0.00
Service	2	0.90	2	0.90	2	0.90
Steering	22	9.91	22	9.91	21	9.46
Studio	1	0.45	1	0.45	1	0.45
Testing	22	9.91	15	6.76	17	7.66
Thermal	27	12.16	17	7.66	22	9.91
Veh Dyn	19	8.56	18	8.11	19	8.56
Weight	14	6.31	12	5.41	6	2.70
Wheels / Tires	18	8.11	10	4.50	16	7.21

Figures multiplied by 100

Table 28. Degree centrality of the actual social network Phase II

	Closeness / Actual Sociogram Phase I		Closeness / Actual Sociogram Phase II	
Engineering Team	**Relative in-Closeness***	**Relative out-Closeness***	**Relative in-Closeness***	**Relative out-Closeness***
Aero	1.59	1.70	1.50	1.69
Architecture	5.78	6.03	4.34	4.84
Attributes	9.95	10.85	9.53	9.98
Body	2.59	3.46	2.54	4.24
Body CAE	2.63	1.83	2.51	1.83
Body Structure	3.92	3.14	4.05	3.93
Brakes	2.41	2.16	1.95	2.55
CAD	2.50	2.20	1.81	1.82
Chassis	8.87	9.64	8.31	9.21
Chassis Supplier	0.90	0.93	0.90	0.93
Chief Engineer	3.80	3.97	3.37	3.16
Durability	1.70	1.76	1.96	1.76
Electrical	8.19	7.80	5.43	5.42
Energy	2.05	1.34	2.26	2.14
Finance	2.04	2.15	1.65	1.34
Integration	5.00	4.39	5.74	4.79
Manufacturing	2.62	2.67	3.35	2.32
Marketing	2.38	2.38	2.37	2.37
NVH	7.84	9.02	7.22	8.17
NVH CAE	0.45	0.86	0.45	0.45
PD_Manuf_L	0.93	0.93	1.26	0.95
Planning	2.17	2.64	2.44	2.22
PM	18.16	17.16	17.70	17.54
Powertrain	6.67	8.17	7.06	8.53
Purchasing	2.50	2.20	2.16	1.80
Quality	1.41	1.41	1.74	1.43
R&D	2.06	1.75	1.96	1.36
Restraint	0.87	0.45	0.81	0.45
Safety	2.05	1.37	2.26	2.15
Sales	0.46	0.45	0.45	0.45
Service	0.96	0.96	0.96	0.96
Steering	2.84	3.41	2.71	2.99
Studio	0.79	0.85	0.75	0.84
Testing	6.60	6.08	6.63	6.86
Thermal	2.94	4.26	3.46	4.23
Veh Dyn	6.14	6.48	5.86	6.41
Weight	1.70	2.16	1.65	2.55
Wheels / Tires	2.50	2.20	3.01	2.98

*** Figures multiplied by 100***

Table 29. Closeness of the actual social network Phases I and II

	Betweenness / Actual Sociogram Phase I		Betweenness / Actual Sociogram Phase II	
Engineering Team	**Betweenness (CB)**	**Relative Betweenness (CB')***	**Betweenness (CB)**	**Relative Betweenness (CB')***
Aero	406	1.66	688.8	2.8
Architecture	301.3	1.23	0.0	0.0
Attributes	9415.6	38.38	8348.7	34.0
Body	0.0	0.00	0.0	0.0
Body CAE	542.0	2.21	497.0	2.0
Body Structure	0.0	0.00	313.5	1.3
Brakes	4811.8	19.62	266.8	1.1
CAD	0.0	0.00	0.0	0.0
Chassis	1973.5	8.04	1026.9	4.2
Chassis Supplier	0.0	0.00	0.0	0.0
Chief Engineer	210.0	0.86	210.0	0.9
Durability	0.0	0.00	5.0	0.0
Electrical	1407.0	5.74	28.0	0.1
Energy	0.0	0.00	74.1	0.3
Finance	0.0	0.00	0.0	0.0
Integration	2206.8	9.00	1039.1	4.2
Manuf	0.0	0.00	944.0	3.8
Marketing	0.0	0.00	0.0	0.0
NVH	2865.2	11.68	2255.3	9.2
NVH CAE	0.0	0.00	0.0	0.0
PD_Manuf_Liason	0.0	0.00	0.0	0.0
Planning	0.0	0.00	0.0	0.0
PM	908.5	3.70	910.0	3.7
Powertrain	819.0	3.34	1181.4	4.8
Purchasing	0.0	0.00	0.0	0.0
Quality	0.0	0.00	0.0	0.0
R&D	0.0	0.00	0.0	0.0
Restraint	0.0	0.00	0.0	0.0
Safety	588.0	2.40	220.5	0.9
Sales	0.0	0.00	0.0	0.0
Service	0.0	0.00	0.0	0.0
Steering	65.0	0.27	1941.9	7.9
Studio	0.0	0.00	0.0	0.0
Testing	1456.7	5.94	2118.4	8.6
Thermal	2807.7	11.45	2679.0	10.9
Veh Dyn	3083.1	12.57	1362.9	5.6
Weight	1396.2	5.69	613.9	2.5
Wheels / Tires	847.7	3.46	1892.7	7.7

***Figures multiplied by 100**

Table 30. Betweenness of the actual social network Phases I and II

9.8. Description of Engineering Teams

The table below provides a brief description of the functions of the engineering teams shown in the theoretical and actual social networks so as to offer a general idea of their responsibilities in the PDP.

Engineering Teams	Responsible for...
Aero	Delivering the Aerodynamics targets
Architecture	Responsible for integrating all vehicle systems into the platform to meet package criteria
Attributes	Integrating the targets of some vehicle attributes
Body	Developing the interior components and systems (e.g., instrument panels, seats, etc.)
Body CAE	Perfoming CAE evaluations of all body-related systems
Body Structure	Developing the structural and external components of the vehicle's body
Brakes	Developing the braking components and systems (e.g., pads, discs, lines, etc.)
CAD	Developing the 3-D geometries of components and systems
Chassis	Developing all chassis related components and systems (e.g. suspension)
Chassis Supplier	Designing and providing chassis-related components and systems to the OEM
Chief Engineer	Leading the overall efforts of the project (engineering, marketing, finance, etc.)
Durability	Delivering the durability vehicle targets
Electrical	Developing all the electrical components and systems (e.g., harnesses, electrical architecture, etc.)
Energy	Assuring the efficient usage of vehicle's resources (e.g., fuel economy, electric loads, etc.)
Finance	Developing the financial plan for the vehicle
Integration	Managing the physical prototypes required for the vehicle level evaluations
Manuf	Delivering manufactured vehicles under the quality

	requirements
Marketing	Defining the marketing plan of the productt under design
NVH	Delivering the Noise and Vibration targets
NVH CAE	Performing NVH-related CAE analyses
PD_Manuf_Liason	Serving as the liason between the PD and Manufacturing teams
Planning	Developing the products strategies
Powertrain	Developing the proper powertrain systems of the vehicle (e.g., calibration, exhaust systems, etc.)
Program Management (PM)	Managing the resources of the project (timing, resources, budget, etc.)
Purchasing	Procuring all vehicle's components and systems
Quality	Assuring the quality targets are met
R&D	Developing the new technologies to be implemented in future vehicle projects
Restraint	Developing the restraint systems (e.g., seatbelts, airbags, etc.)
Safety	Delivering the Safety targets
Sales	Defining the sales strategy
Service	Assuring the serviceability of the product
Steering	Developing the steering components and systems
Studio	Desigining the overall styling of the vehicle (e.g., interiors, exteriors)
Testing	Testing the different areas of the vehicle
Thermal	Delivering the Heat Management and Powertrain Cooling targets
Veh Dyn	Delivering the Vehicle Dynamics targets
Weight	Tracking and delivering the vehicle's weight
Wheels / Tires	Delivering the appropriate wheels and tires

Table 31. Description of Engineering Teams

9.9. Questionnaire for Actual Sociograms Construction

Thank your participating in this survey. Your feedback will be important to understanding how information flows in a global vehicle program. Your responses will be kept confidential.

1. Name

2. Work experience:

0-5 years *6-10 years* *11-15 years* *16-20 years* *21 years or more*

Questions 3 and 4 refer to interactions that you had during the First Design Phase

3. For your current project / program, list 5 to 10 persons from whom you have received the most input for completing your tasks (include members of other Engineering teams and/or international sites if applicable) - *The second column is optional.*

Name	Type of Information (e.g., Design Parameters, Testing Plans, Costs, etc.)

4. For your current project / program, list the 5 to 10 persons to whom you must provide the most information for completing their tasks (include members of other Engineering teams and/or international sites if applicable) - *The second column is optional.*

Name	Type of Information (e.g., Design Parameters, Testing Plans, Costs, etc.)

Questions 5 and 6 refer to interactions that you had during the Second Design Phase

5. For your current project / program, list 5 to 10 persons from whom you have received the most input for completing your tasks (include members of other Engineering teams and/or international sites if applicable) - *The second column is optional.*

Name	Type of Information (e.g., Design Parameters, Testing Plans, Costs, etc.)

6. For your current project / program, list the 5 to 10 persons to whom you must provide the most information for completing their tasks (include members of other Engineering teams and/or international sites if applicable) - *The second column is optional.*

Name	Type of Information (e.g., Design Parameters, Testing Plans, Costs, etc.)

Thank you very much for your support.

9.10. Sociograms based on Engineers' IDs

The labels of the sociograms presented below are based on an ID assigned to each engineer of the organization. The way the labels were constructed is exemplified in the next diagrams:

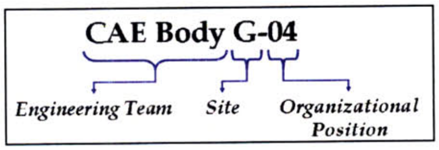

Figure 55. Construction of engineers' id - Option 1

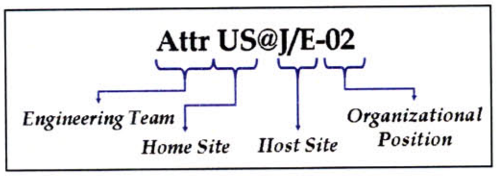

Figure 56. Construction of engineers' id - Option 2

Figure 56 basically applies to actors in international assignments. In the case depicted in the figure, the engineer belongs to the US organization, but for the duration of the program is located either in Japan or in Europe.

The tables presented next can be used as a reference to construct the IDs:

Sites	
Label	**Definition**
G	Germany
US	United States
J	Japan
GB	Great Britain
SA	South Africa
MX	Mexico
T	Taiwan
AUS	Australia
CHN	China
THA	Thailand
E	Europe
IN	India

Organizational Position	
Number	**Position**
0	Chief or Director
1	Manager
2	Supervisor
3	Technical Specialist or Technical Leader
4 and above	PD Engineer

Table 32. IDs for sociogram labeling (Engineering Sites and Organizational Position)

Engineering Teams		Engineering Teams		Engineering Teams	
Label	**Definition**	**Label**	**Definition**	**Label**	**Definition**
PM	Program Management	Electric	Electrical Systems	R&D	Research & Development
Aero	Aerodynamics	EM	Engineering Manager	Restraint	Restraint
Arch	Architecture	Energy	Energy Management	Safety	Crash and Safety
Assit	Chief Engineer Assitant	Finance	PD Finance	Sales	Product Sales
Attr	Attributes	Int	Integration	Service	Product Service
Body	Body Interior	Manuf	Manufacturing	Steering	Steering Systems
Body	Body Structure	Mkt	Marketing	Studio	Design Studio
Brakes	Braking Systems	NVH	Noise & Vibration Harshness	Test	Testing
CAD	CAD Engineering	PD_Manuf_L	Liason PD & Manufacturing	Thermal	Thermal Engineering
CAE Body	CAE Body Structure	Pilot	Pilot Plant	Tires Suppl	Tires Supplier
CC	Change Control (part of PM)	Planning	PD Planning	Trans Cal	Transmission Calibration
CE	Chief Engineer	Platform	Vehicle Platform	Veh Dyn	Vehicle dynamics
Chassis	Chassis	PT	Powertrain	Weight	Weight Engineering
Chassis Suppl	Chassis Supplier	Purchase	Purchasing	Wheels Suppl	Wheels Supplier
Dur	Durability	Quality	Product Quality	Wheels_Tires	Vehicle Wheels and Tires

Table 33. IDs for sociogram labeling (Engineering Teams)

Below, the sociograms for *Phases I* and *II* with the engineers' ID are presented:

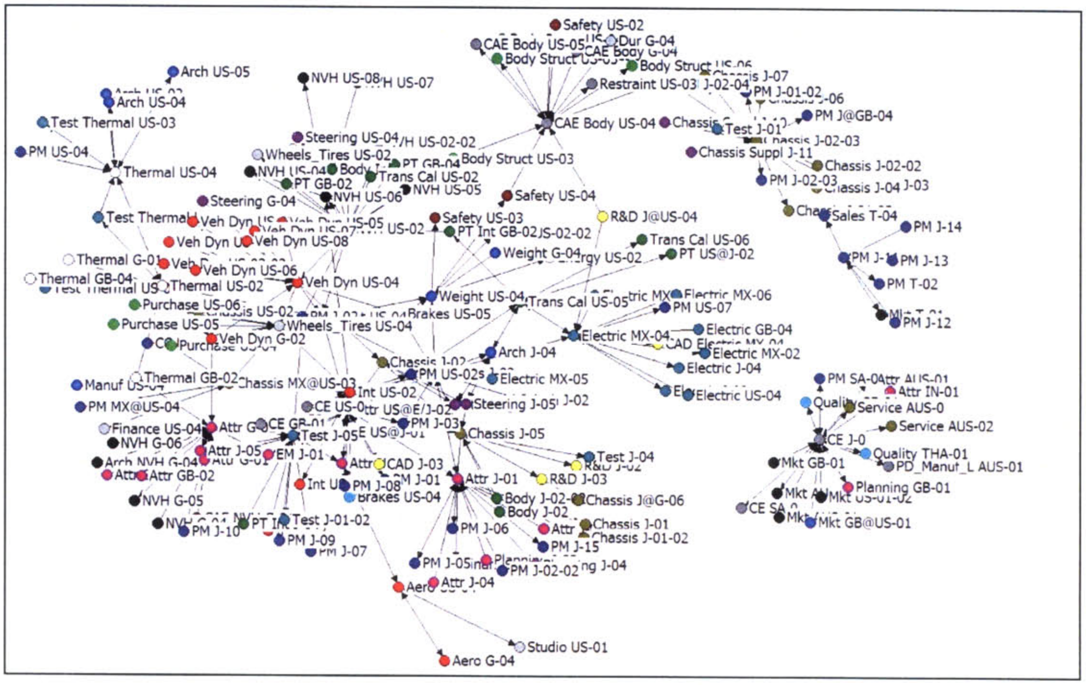

Figure 57. Sociogram for Phase I based on the engineers' ID

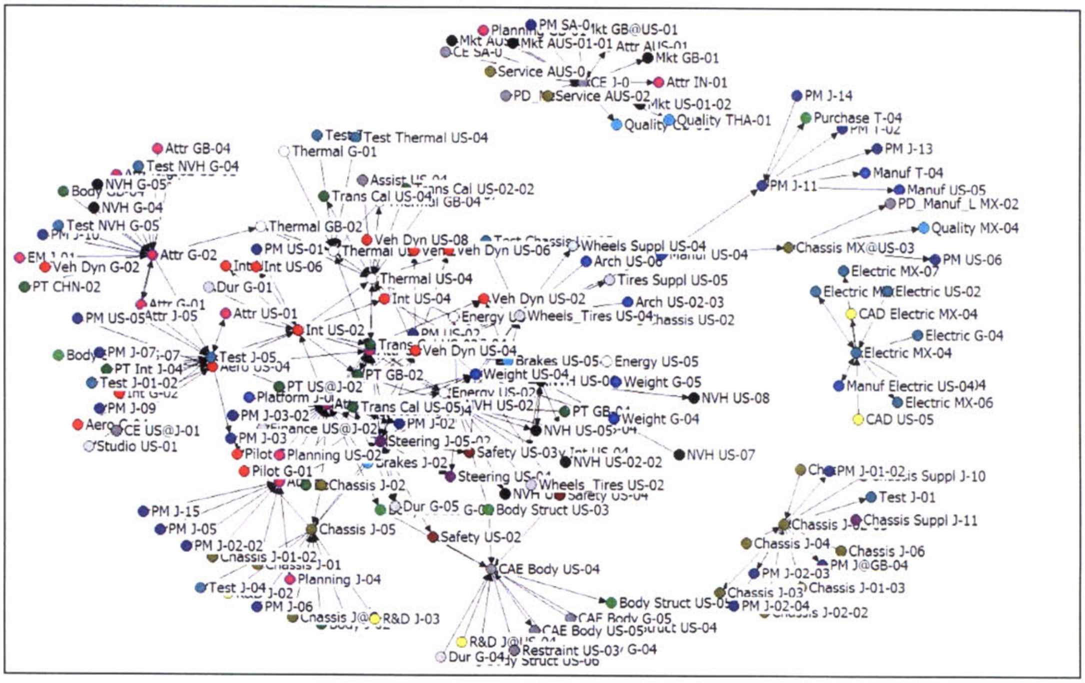

Figure 58. Sociogram for Phase II based on the engineers' ID

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