Impact of Technology Readiness in the Development of Automotive Systems when incorporating New Styling: a Graph Theory Approach to OPM hierarchical Decomposition of the System's Architecture

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Dedicated to Martha, my mother.

From whom I have discovered the sound of a true voice...

... from whom I have learnt the essence of my voice.

The development of automotive systems with new styling and technological content: a dynamic structure of people and activities

By

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Abstract

This thesis addresses to find whether technology readiness, while developing a system of new derivative vehicles, has an influence on the time required to design a part that involves styling and engineering activities. For doing so Styling Level and Technology Readiness were identified as independent variables, whereas Styling Iterations and Styling Iterations Time were designated as the dependent variables. In this case, the tools used to confirm correlation among variables were simple and multiple linear regressions. As it will be further detailed, Styling Iterations Time had the highest response to Technology Readiness while the rest of variables had no significant correlation on time duration for Studio and Engineering design activities.

Based on hypothesis results and using OPM hierarchical decomposition, relations between processes and objects were analyzed at a given design state in order to evaluate complete matching relying on bipartite graphs and Hall's *Marriage* theorem. In addition, it was outlined how to identify delayed processes that fail to coexist due to a low technology readiness at a given design state using the Four-Colour theorem and elaborating about the application of chromatic number and polynomials to the OPM system's architecture.

The system of interest was the headlamps system developed under Ford Global Product Development System (GPDS) using the Global Exterior Lighting Plan (PDP).

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My sister Nayeli for subtlety teaching me how to be brave in life.

My cousin Dulce, who today would be my same age, whose departure taught me how strong and united my family can be.

My family, with whom I feel truly happy when sharing simple moments while immersed in a warm conversation.

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List of Acronyms

3D	Three-dimensional
3EC	Third Engineering Concept
AA1	Appearance Approval 1
CAD	Computer-aided Design
DSM	Design Structure Matrix
eSCR	Electronic Surface Change Request
FAA	Final Appearance Approval
FDJ	Final Data Judgment
GPDS	Global Product Development System
OPD	Object-Process Diagram
OPM	Object-Process Methodology
PA	Program Approval
PDP	Perfect Drawing Plan
PT	Powertrain
SDM	System Design Management
SI	Styling Iterations
SIT	Styling Iterations Time
SL	Styling Level
TR	Technology Readiness
UN	Underbody
UP	Upperbody

Chapter 1 | Introduction

A straight-line is said to have been cut in extreme and mean ratio when as the whole is to the greater segment so the greater (segment is) to the lesser.

Euclid, *Elements – Book 6, Proposition 2*

Science! True daughter of Old Time thou art!

Edgar Allan Poe, *Sonnet – To Science*

At Ford it has been a common practice to develop simultaneously vehicles that address customer wants and needs through a product that incorporates both a design interpretation, and a set of technological solutions. Hence, automotive systems, which have a strong interaction between Studio and Engineering activities, are evolved under the assumption that vehicles sharing the same development scalability can be encapsulated within the same timing frame regardless of differences in technology readiness aspects.

As suggested by De Weck-Roos-Magee that automobile industry can be considered as a window to understand changes of things functioning in the epoch of engineering systems [1], it represents then a great opportunity to study the development of vehicle parts where the activities mentioned above take place. In this case the vehicle headlamps, which is one of the most complex automotive parts given that it must communicate an aesthetic design attitude while including technological elements to ensure its expected function, constitutes the system that will be the subject matter of this thesis.

An engineering systems approach has been considered to analyze the headlamps system as an attempt to delve into its architecture regarding styling and engineering processes that are critical for its completion. Likewise, the hierarchical decomposition of the headlamps system was connected with its technology readiness by using graph theory concept to elaborate a way to organize processes having a risk to interfere with each other because of delayed circumstances during development.

1.1 | Motivation

After almost ten years of work experience at Ford where I had had the opportunity to participate in the development of vehicle programs from different angles such as engineering, CAD design, and more recently with a liaison role between Body Exterior functional and management areas, I have perceived that development assumptions have impacts on the system's architecture of the part being developed. Specifically, it was during the development of vehicles Expedition and Navigator 2015 that I noticed that although the same scalability was assigned to both programs, these had difficulties to achieve the same timing when developing parts that apparently were common between vehicles specifically for those deliverables that required collaboration between Studio and Engineering. These observations made me inquire what factors could explain such development differences.

Furthermore, having the privilege and honor to be part of the System Design and Management (SDM) Program at the Massachusetts Institute of Technology (MIT), exposed me to a caudal of impressive and superb skills and knowledge that helped me to address, to the best of my capacity, the development scenario just described above. Without any doubt, the two foremost ideas and concepts that provided foundation to this thesis were the hierarchical decomposition of a system [2] from a systems architecture view [3], and the incorporation of graph theory of which I realized its applications while reading about structure of systems considering an Engineering Systems frame of reference [1].

Finally, it is altogether fascinating to propose future ways to design and develop automotive systems with inherent complexity that meet not only customer expectations, but also sociotechnical aspects so to enable more effective dialogues among team members. Although challenging, such improvements facilitate the convergence of human, design and technology elements required to make tangible a new vehicle.

1.2 | Thesis Objective and Hypothesis

The following thesis has as a main purpose to elicit the effect of Technology Readiness versus Styling Level on time duration of processes that require Studio and Engineering coordinated activities during the development of a new vehicle system. In addition, it is intended to contextualize the impact of technology readiness effect on the architecture of the system so to have, on the one hand, an understanding of alterations to the relations between processes and objects, and on the other hand, delineate a method to assign specific work streams to conflicting processes that are delayed because of a technology readiness situation.

The hypothesis of this thesis takes into account the development of systems of derivative vehicles that bring together Studio and Engineering so to have final design intent of the product and general influence of technology readiness during progress of the system:

Headlamp system derivatives belonging to a common platform with different technology readiness levels will have difficulty achieving the same timing during Studio & Engineering design iterations.

Based on hypothesis findings, the following question is attempted to be answered:

How processes that have a high risk to be delayed due to technology readiness factors can be assigned to categories or work streams in order to better address them?

1.3 | Research Methods

The methodology followed to test the hypothesis of this thesis was to identify critical variables regarding technology readiness and time completion for surfaces changes to parts that require collaboration between Studio and Engineering. In this case, the variables were Styling Level (SL), Technology Readiness (TR), Styling Iterations (SI), and Styling Iterations Time (SIT) that will be defined in subsequent chapters. The system of interest is Exterior Headlamps and ten Ford vehicle programs were selected to carry out observations.

The main measurement system utilized was the Surface Change Request that stores the record of surface updates submitted electronically (eSCRs) by the team participating in the program. In regard to headlamps hierarchical decomposition as a system, it was used the OPM Hierarchical Decomposition Template [2] combined with Crawley-Cameron and Dori concepts [3], [4].

With respect to determination of correlation among variables it was used simple and multiple linear regressions, which results obtained, were later studied using graph theory concepts [5].

1.4 | Thesis Structure

The following summary helps to delineate the cadence of the thesis and provide the reader an outline of chapters to indicate how the hypothesis and question mentioned before are intended to be tested and answered, respectively.

Chapter 2 | OPM Hierarchical Decomposition of Headlamps PDP System and Concept of OPD Bipartite Graphs

Concepts of system architecture are reviewed to have a sense of how do processes and objects interact during the design and engineering of a product, in this case the headlamps system, within the Ford product development vision. In addition, the graph theory concepts or bipartite graph and Hall's *Marriage* theorem complement the notion of complete match between behaviors and forms of a system with the intention to realize how assumptions while developing an automotive part impact the system´s architecture.

Chapter 3 | Impact of Styling Level and Technology Readiness Concepts

Definitions of central variables studied SL, TR, SI, and SIT are provided. Likewise, linear regressions are carried out with the rationale to establish correlations among variables and test acceptance or rejection of main hypothesis of the thesis. Additionally, the model, contour plot, and surface plot of multiple linear regression are shown to complement the influence of each variable identified.

Chapter 4 | Application of OPM Decomposition and Four-Colour Theorem to Headlamps System based on hypothesis results

The concepts of system architecture and graph theory concepts are resumed incorporating findings of multiple linear regression so to attempt to answer the question regarding work streams assignments. To do so, Four-Colour theorem and chromatic number and polynomial notions from graph theory complement the hierarchical decomposition of the headlamps system.

Chapter 5 | Conclusions and Final Recommendations

This chapter contains critical findings emphasizing the importance of the technology readiness multiple regression model and its application to an automotive part development. In the same way, it is encouraged to consider other systems at Ford that need a dialogue between Studio and Engineering dialogue develop a product and general opportunities are mentioned to take into account in regard to GPDS improvement. Finally, it is suggested to continue delving into system architecture and graph theory concepts so to keep refining Product Development System at Ford.

Chapter 2 | OPM Hierarchical Decomposition of Headlamps PDP System and Concept of OPD Bipartite Graphs

If I am to know an object, though I need to know its external properties, I must know all its internal properties.

Ludwig Wittgenstein, *Tractatus Logico-Philosophicus*

Como todas las palabras abstractas, la palabra *metáfora* es una metáfora, ya que vale en griego por traslación.

Jorge Luis Borges, *Nueve Ensayos Dantescos – Purgatorio 1, 13*

The system's architecture of the headlamps of a new vehicle, studied at a certain point of time during its development, constitutes the cornerstone for the subsequent analyses that construct the embodiment of reflections and results to be later discussed in this thesis. Provided literature related to system architecture is vast, it has been considered the perspective of decomposing hierarchically [2] the objects (Forms) and the processes (Behaviors), from current Global Exterior Lighting PDP used at Ford, that are required to deliver the main function of the headlamps system.

For the purpose of providing a picture of the system's condition it is utilized the Design state, *Ds* concept [2], delineated by the Context and Requirements sets *C* and *R*, respectively. Additionally, the semantics and graphical language used to depict system architecture concepts have been taken from Crawley-Cameron SDM course [3], which incorporates most of the principles of object-process methodology (OPM) elaborated by Dori [4], with a specific focus on object-process diagrams (OPDs).

OPDs have the characteristic that allows them to be treated as bipartite graphs, which are a concept from graph theory, and that will be used to evaluate the *marriage* required between Forms and Behaviors examined at a given stage of progress of the headlamps system. As it will be further explained the *marriage* notion relies as well on a theorem of graph theory and the intention to bring it is to assess that Forms have their corresponding Behaviors to continue moving forward in terms of development maturity.

2.1 | Description of PDP and GPDS

The PDP is a timed compilation of processes and deliverables that need completion so to develop the headlamps system for a new vehicle according to a pre-established scalability and timing driven by the process logic of GPDS. It is executed globally by the Exterior Lighting teams and also illustrates the enablers that need to occur among key stakeholders such as Purchasing, Studio, Craftsmanship, Program Management, and Supplier from a perspective of what is necessary to be given and received by Exterior Lighting during the evolution of the headlamps system.

Referring to GPDS, this is the product development system globally followed to deliver a new vehicle and it encompasses as well the Vehicle and Powertrain milestones through the gateways of Studio, Engineering, Prototype, and Build stages. By the same token, GPDS includes the pertinent considerations for scaling a new vehicle program based on the content change for Upperbody (UP), Underbody (UN), and Powertrain (PT) being UP of particular interest given the interactions between Engineering and Studio to transform a styling surface into an actual part of a new vehicle's system.

Figures 1 and 2 show a fragment of current PDP and GPDS, respectively, used at Ford intentionally emphasizing similar phases of development to appreciate alignment between PDP with respect to GPDS.

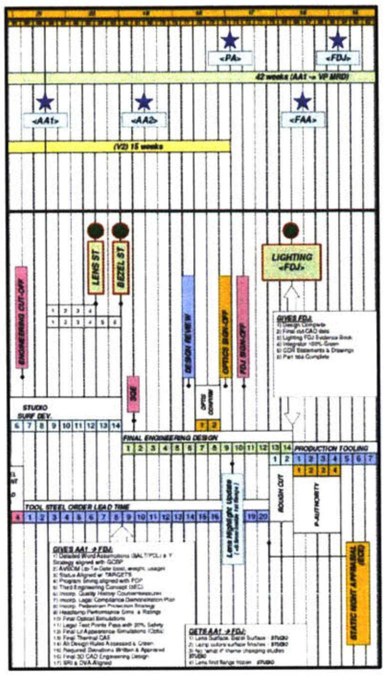


Figure 1. Global Exterior Lighting PDP

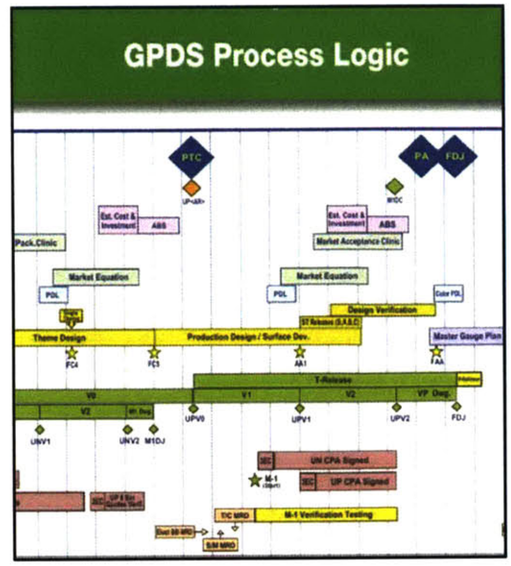


Figure 2. GPDS AA1 – FAA/PA – FDJ Detail

2.2 | Overview of System Architecture, OPM, and OPD

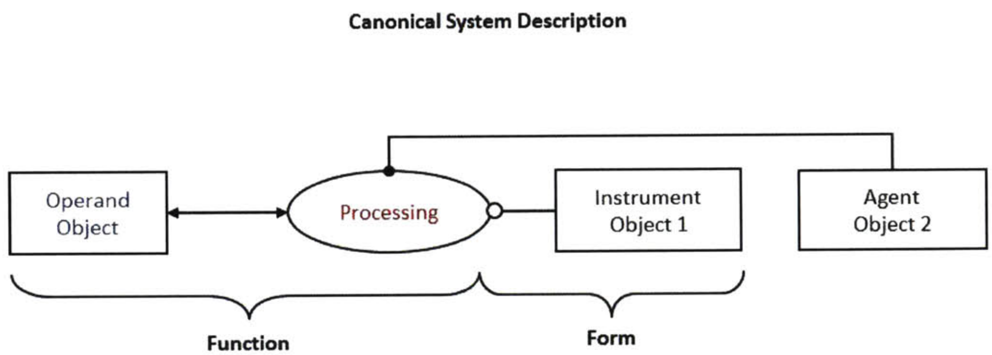
System architecture is a broad discipline, so the following preliminary definitions and graphical nomenclature presented in Figure 3, based on Crawley-Cameron lecture notes [3], support the concepts to be covered in this chapter:

- OPM: is a system development methodology that integrates many system attributes in one model.
- OPD: graphical representation of objects, processes, and links (structural and procedural) of a given system's architecture.
- Object: that which has the potential of stable, unconditional existence for some positive duration of time. Objects can be physical or informational.
- Operands: those objects whose state is changed by a process.

- Agents/Instruments: those objects that execute the process, and whose state is not (substantially) influenced by the process.

- Process: the pattern of transformation applied to one or more objects. Processes change the state of an object.

- State: is a situation at which the object can exist for some positive duration of time (and implicitly can change).



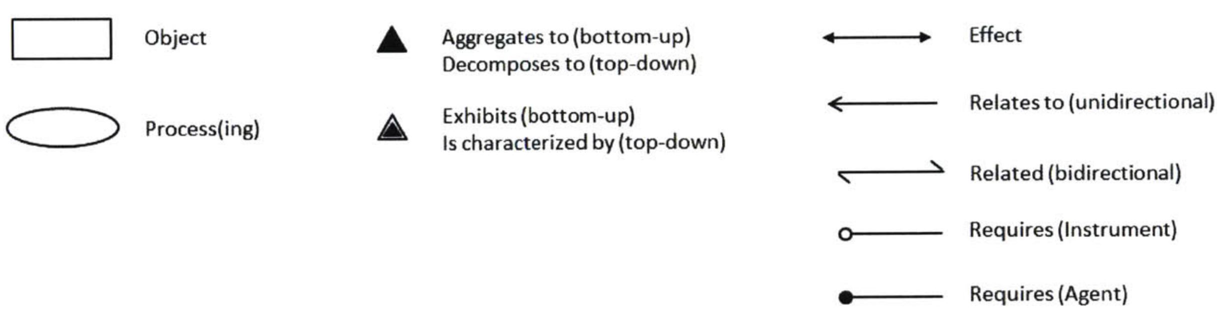


Figure 3. OPM/OPD Graphical Nomenclature [3], [4]

The canonical system description is formally read as: Process effects operand, with object 1 as an instrument and object 2 as an agent2. In a similar manner, the following statements exemplify it:

- Headlamps are developed by Exterior Lighting Engineering. (Agent)
- Headlamps styling surfaces are designed with 3D rendering software. (Instrument)

Based on previous definitions and Figure 3, the function of a system's architecture is the result of the combination among operands and processes plus instrument objects (form) and/or agents (objects).

2.3 | Application of OPM Decomposition Template to Headlamps system

System architecture and specifically OPM provide the fundamental semantic and graphical platform to decompose a system or domain [2]. Such an exercise, although abstract in essence, helps to understand in a comprehensive way the function of a system and it is fulfilled through identifying the Forms that, on the one hand, represent what the system is, and the Behaviors that, on the other hand, illustrate how the system operates to accomplish its goal or its main function given that a transformation of Form(s) occurs. In a similar manner, OPM, through OPD representations, provides a language to interpret relationships between Forms and Behaviors contained within the different sets of the system.

A system undergoes a number of design states during its development that can be analyzed at any given instant in time by means of the design state *Ds* that comprehends the requirements set *R*, the context set *C*, and the system set about to be designed *S*. In addition, R and C are required inputs to the parameters of the system *S* [2]. Thus, *Ds* is an instantly descriptive measure obtained from the sets *R*, *C*, and *S* expressed as $Ds = \{R, C, S\}$ that can be represented using the OPM decomposition template shown in Figure 4 [2]. By this way, it is possible to analyze the *Ds* of the combination of Form-Behavior, which added together support the system to achieve its function while operating, with respect to the system's requirements *R* for a given context *C*.

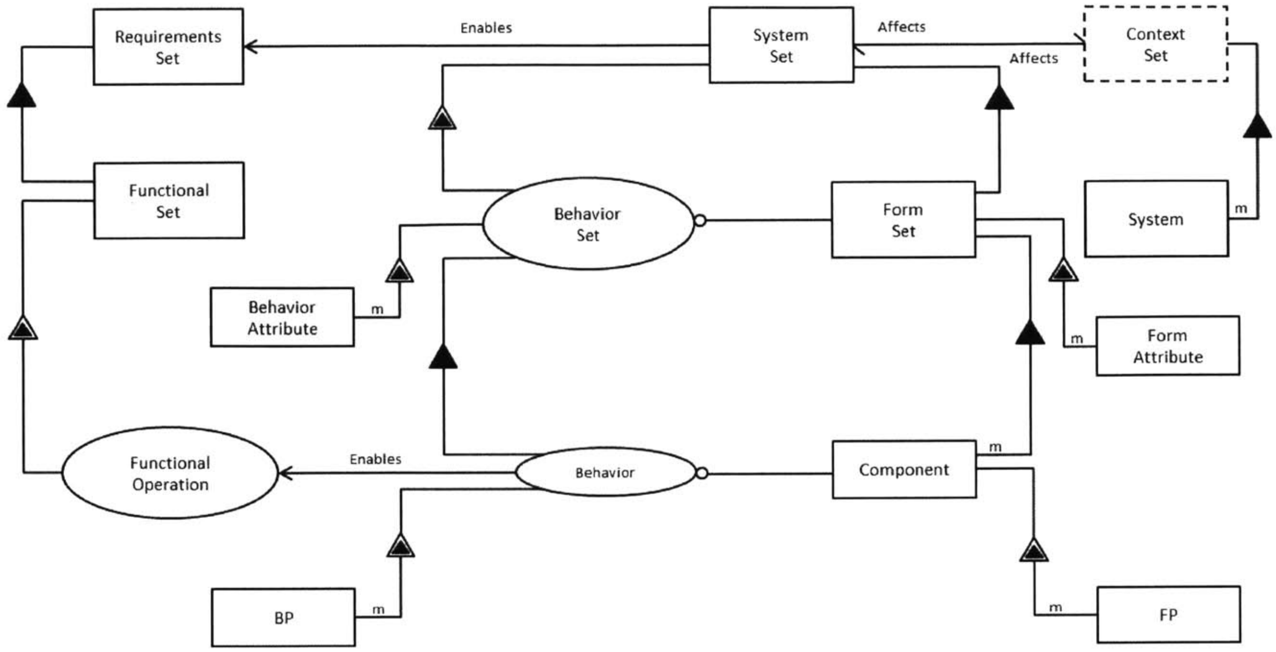


Figure 4. OPM Decomposition Template [2]

Figure 5 illustrates the actual application of OPM decomposition template to the headlamps system. In this case, the design state *Ds* has been chosen during AA1 and FAA from Studio gateways, a period that intersects PA and FDJ Vehicle milestones. The reason for focusing on this *Ds* is that during this instant of development there are critical processes that impact not only the engineering headlamps system, but also the commercial and supplier's manufacturing systems.

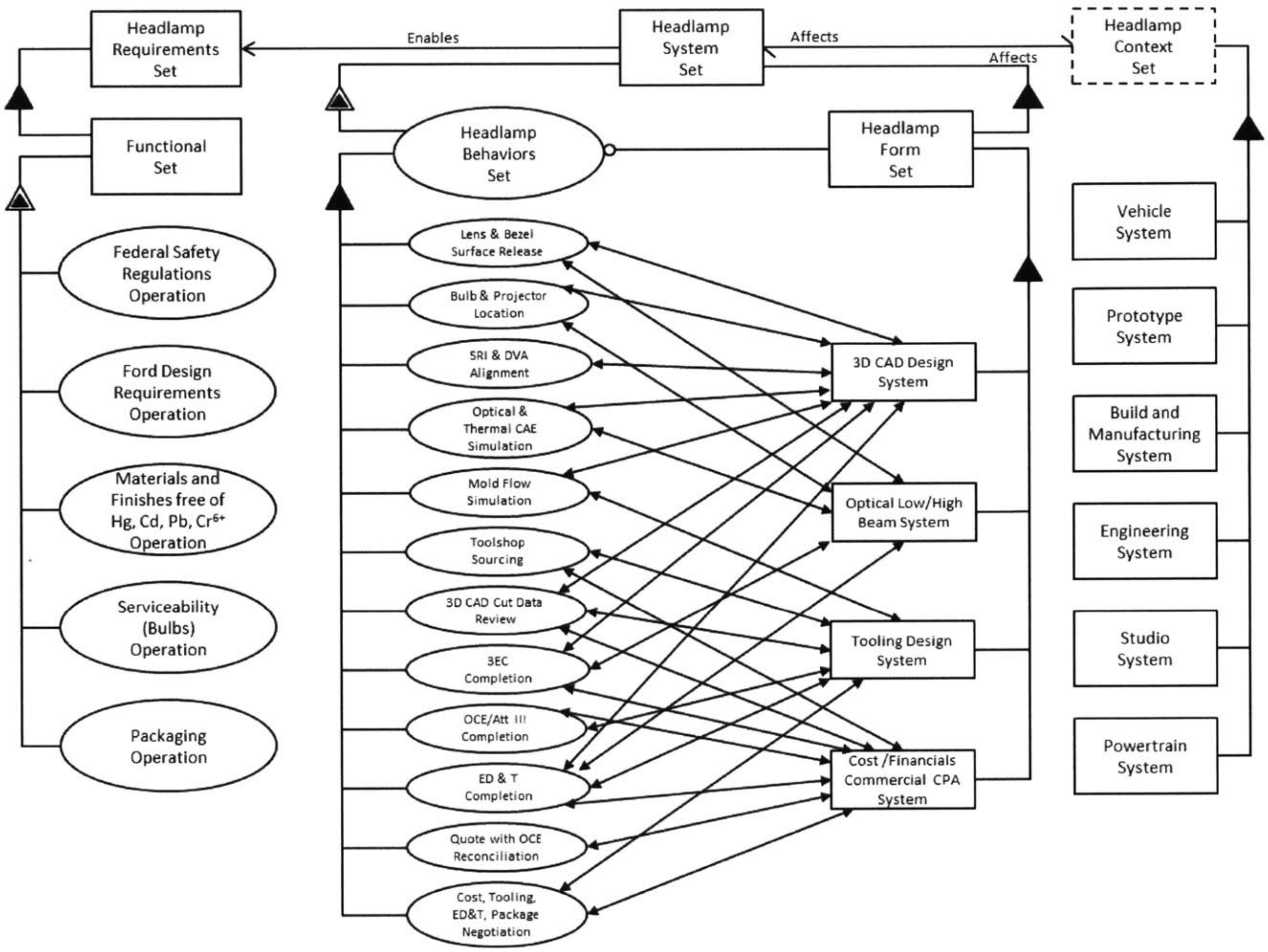


Figure 5. OPM Decomposition of Headlamps System

The headlamps requirements set decomposes to the functional set, which is characterized by the operation of federal safety regulations, Ford core engineering requirements, materials and finishes free of Hg, Cd, Pb, and Cr^{6+}, serviceability of bulbs, and packaging with respect to other systems. In regard to the headlamps context set, this decomposes, on the one hand, to Powertrain and Vehicle milestones, and the other hand, to the Studio, Engineering, Prototype, and Build gateways as indicated in GPDS.

Concerning headlamps behavior set, this is decomposed to twelve processes that vary from releasing Studio surfaces, locating bulb and projector, accomplishing diverse CAE simulations, sourcing of toolshop to final negotiation of ED&T and cost, among others. These processes are related to the four systems that aggregate to the headlamp form set that includes 3D CAD design, optical strategy, tooling design, and commercial (cost/financials).

2.4 | General Definitions of Graph Theory

As previously mentioned, OPDs behave as bipartite graphs from a graph theory perspective and the correspondence between objects and processes can be also examined through Hall's theorem. The following definitions and Figure 6, based on explanations by Wilson [5], provide a foundation for concepts to be discussed in this and posterior chapters:

- **Simple Graph:** a graph G that consists of a non-empty finite set $V(G)$ of elements called vertices (or nodes or points) and a finite set $E(G)$ of distinct unordered pairs of distinct elements of $V(G)$ called edges (or links).
- An edge $\{v,w\}$ joins vertices v and w and it is abbreviated as vw.
- Two vertices v and w are **adjacent** if there is an edge vw joining them, and the vertices v and w are then **incident** with the edge vw.
- **Degree** of a vertex v: is the number of edges incident with v and it is written as deg(v).
- **Loop:** an edge joining a vertex to itself.
- **Multiple edges:** a pair of vertices that are joined by several edges.
- **General Graph:** a graph G that allows loops and multiple edges.
- **Connected Graph:** a graph G is connected if it cannot be expressed as a union of graphs, if not, it is a disconnected graph.
- $G - e$: is the graph obtained from G by deleting the edge e.

- $G - v$: is the graph obtained from G by deleting the vertex v together with the edges incident with v.

- $G \setminus e$: is the graph obtained from G by taking an edge e and "contracting" it; in order to contract e, its end vertices v and w need to be identified so that the resulting vertex is incident with all those edges that were originally incident with v or w without considering e.

- **Complete Graph**: a simple graph in which each pair of distinct vertices are adjacent. A complete graph of n vertices is denoted as K_n.

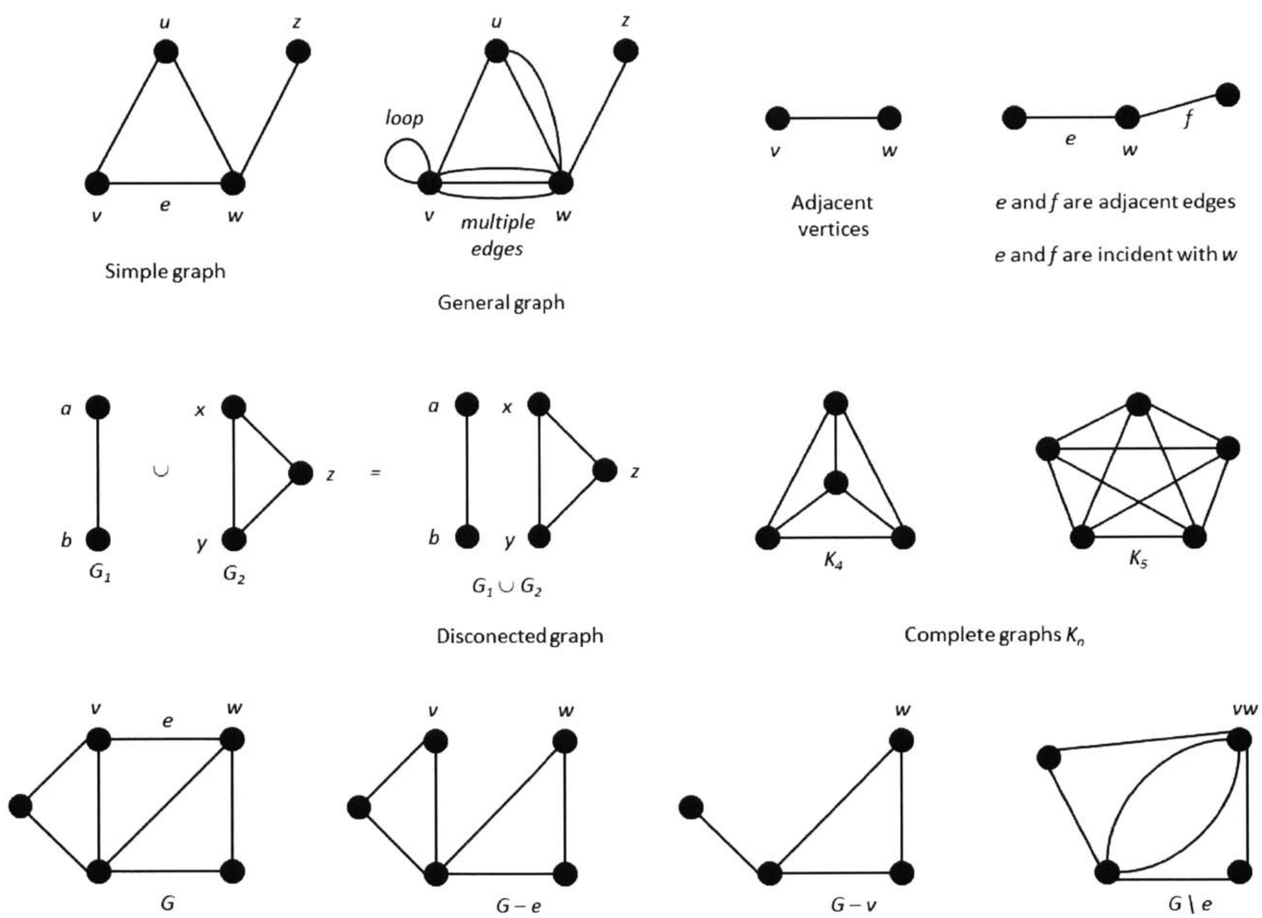


Figure 6. Graph Theory Concepts [5]

2.5 | Definition of Bipartite Graphs

Taking into account definitions presented above and Figure 6, there is sufficient background to introduce the concepts of bipartite graph and Hall's theorem according to Wilson [5].

If the vertex-set of a graph *G* can be split into two disjoint sets *A* and *B* in a manner that each vertex of *G* joins a vertex of set *A* with a vertex of set *B*, then *G* is a **bipartite graph**. Furthermore, a graph *G* is bipartite if its vertices can be coloured black and white such that each edge joins a black vertex from set *A* to a white vertex from set *B*. A bipartite graph is usually written as *G = G(A, B)*.

In a similar manner, a **complete bipartite graph** is a bipartite graph in which each vertex of *A* is joined to each vertex of *B* just by one edge. A complete bipartite graph is designated with *r* black vertices and *s* white vertices by $K_{r,s}$.

Figure 7 exemplifies the idea behind bipartite and complete bipartite graphs.

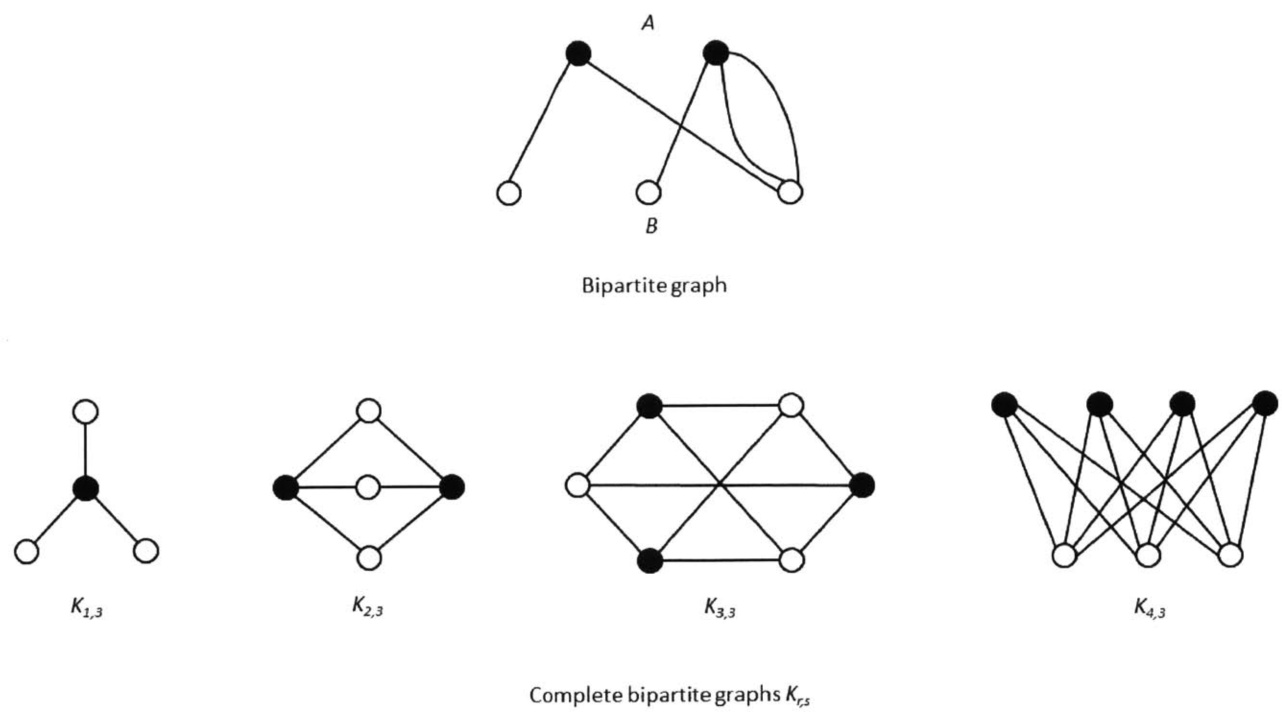


Figure 7. Bipartite and Complete Bipartite Graphs Concepts [5]

2.6 | Hall's *Marriage* Theorem

Hall's *Marriage* theorem addresses the following question [5]:

If there is a finite set of girls, each of whom knows several boys, under what conditions can all the girls marry boys in such a way that each girl marries a boy that she knows?

Figure 8 exemplifies the friendships between the two disjoint sets V_1 and V_2 of girls $\{g_1, g_2, g_3, g_4\}$ and boys $\{b_1, b_2, b_3, b_4, b_5\}$, respectively.

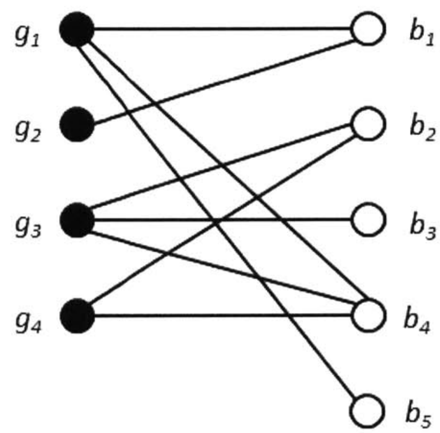


Figure 8. Girls – Boys Friendships Bipartite Graph Example [5]

In general, a complete matching from V_1 to V_2 in a bipartite graph $G(V_1, V_2)$ is a one-to-one correspondence between the vertices in V_1 and some of the vertices in V_2, in such a way that corresponding vertices are joined. Thus, the *marriage* problem in graph theory language can be stated as:

If $G = G(V_1, V_2)$ is a bipartite graph, when does there exist a complete matching from V1 to V2 in G?

Any solution to the *marriage* problem needs to satisfy the *marriage condition* [5] that indicates:

Each set of k girls must know collectively at least k boys, for all integers k satisfying $1 \le k \le m$, where m is the total number of girls.

Considering the *marriage* condition, the Hall's *Marriage* theorem can be stated as [5]:

- *Theorem: A necessary and sufficient condition for a solution of the marriage problem is that each set of k girls collectively knows at least k boys, for $1 \le k \le m$.*

2.7 | Application of Hall's *Marriage* Theorem to OPM decomposition of Headlamps System at a hypothetical design state *Ds*

So far the OPM decomposition of the headlamps system, which provides a picture of the system's architecture at a given instant of development, allows to have a deep comprehension in regard to the design state *Ds* of the system. It is natural to assume that Forms and Behaviors match each other because these follow the planned progression of a system, in this case, the headlamps of a new vehicle. Nonetheless, when processes and objects are delayed, then the matching between the Behaviors and Forms of the two disjoint sets of the system's OPD might start to reveal that *marriage* condition is not being satisfied. Furthermore, this situation is aggravated when delayed Behaviors and Forms of a previous design state Ds_1 start to interfere with a posterior Ds_2.

Without exploring at this moment what independent variables might have an impact on the development of the headlamps system and for illustrating purposes of application of Hall's *Marriage* theorem, it is evaluated the OPD bipartite at a hypothetical *Ds* during FAA GPDS stage assuming that the process of Bulb and Projector Location has not being accomplished. The bipartite graph $G = G(F, B)$ considers F and B as the disjoint sets for Forms and Behaviors, respectively.

Figures 9 and 10 show the resulting OPD of the headlamps system and its simplified bipartite graph, respectively. In this case, a complete match among Forms and Behaviors cannot take place given that the *marriage* condition is not satisfied because Forms f_3 and f_4 have in common the candidate Behavior b_3, hence not satisfying the inequality $1 \le k \le m$.

This type of hypothetical situation helps to visualize the effects of an activity that is related to technology feasibility rather than to styling level (SL) on the development of the headlamps system, and, moreover, how technology readiness (TR) may have an inherent repercussion on the system's architecture at a given design state *Ds*.

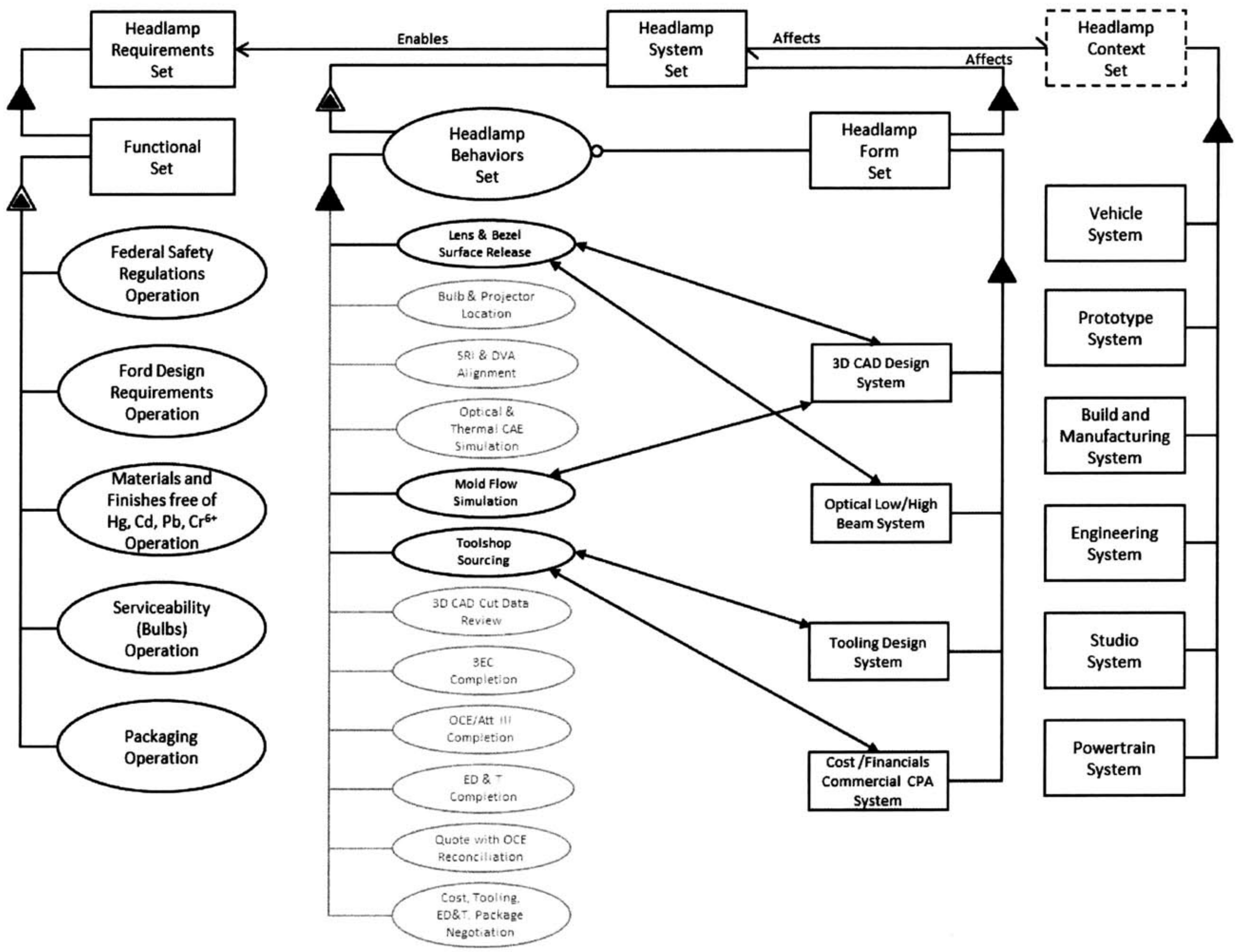


Figure 9. Application of Hall's Theorem to Headlamps OPM

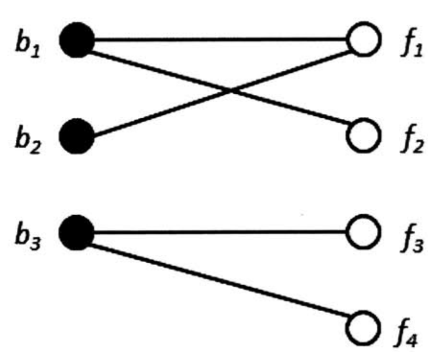


Figure 10. Application of Hall's Theorem to Headlamps OPM (Bipartite Graph)

Chapter 3 | Impact of Styling Level and Technology Readiness Concepts

The shape of today's automobiles is derived from the placement of the engine (under the hood) and was a natural evolution from its predecessor, the horse and the carriage.

... Whenever a radically new architecture emerges, there are opportunities to explore hitherto unimagined technical solutions and forms.

Mitchell, Borroni-Bird, Burns, *Reinventing the automobile*

The OPM decomposition of the headlamps systems at a given design state *Ds* and the analysis of the resulting OPD, from a bipartite graph perspective and Hall's *Marriage* theorem application, help to describe the operation of the system's architecture. This examination assumes the presence of factors that influence the development of the headlamps system that could be translated into either amount or duration of work. In a certain way, the potential factors or candidate independent variables just implied have already been mentioned at the end of chapter 2 that are in this case styling level (SL) and technology readiness (TR). In addition, the variables that might be affected are styling iterations (SI) and styling iterations time (SIT).

In view of above, the concepts SL, TR, SI, and SIT, together with GPDS scalability of a new vehicle, need to be clearly defined in order to establish and test the main hypothesis of the present thesis. In this case, simple linear and multiple regressions have been the tools used to find correlations between variables, and these were applied to a number of programs that either have been already or are being developed at Ford. The system of interest is, once more, the exterior lighting headlamps.

Chapter 3.1 | Definition of Scalability (GPDS) and Variables SL, TR, SI, and SIT

Ford GPDS scalability for a new vehicle is based on the content changes that the product will have in regard to UP, UN, and PT. So, a vehicle scaled as 654 means that its scalability is 6 for UP, 5 for UN, and 4 for PT, respectively. Each of the scales has a precise description of the content change as shown in Table 1 for UP case. The case of UP scale has a double purpose within the management of a new vehicle, on the one hand, designates a metric to establish timing development and resources to be assigned to the program, and on the other hand, it sizes the interaction that Engineering and Studio will maintain during the development and styling of surfaces that are required to design system parts that have to comply not a functional, but an aesthetic requirement as well.

Table 1. GPDS UP Content Change Description

Scale	UP
6	All New
5	Carry-over Structures and New In/Out body
4	Carry-over Inner Body, New Outer Body, and New Lamps
3	New Bonnet, Fender, Liftgate, Carry-over Bodyside, and Side Closures, Constrained Lamps Change
2	New Bumper and Grill
1	Badge Work

The following definitions enlisted summarize the variables that have been identified as crucial for hypothesis statement and its further test:

- **Styling Level (SL):** Independent variable that directly refers to the UP scale assigned to a new vehicle in regard to its content change. It represents the final appearance of an exterior system, such as Headlamps, and encapsulates the Ford DNA aesthetic design imprinted by the Studio group. SL is a dimensionless variable given that it is based in GPDS UP scalability, which does not have an associated specific unit.

- **Technology Readiness (TR):** Independent variable that is related to availability of components, compatibility with surrounding interfaces, completion of legal requirements, and incorporation of styling lighting signature. Moreover, it comprises light sources already developed that, together with supplier's manufacturing existent processes, weighs how accessible, from a technological angle, and ready to be developed is the current design state Ds of the headlamps system. Although TR is a dimensionless variable, its value is obtained through an evaluation from a seven questions questionnaire that will be presented in the next section.

  This variable brings together the design constraints currently enlisted in exterior lighting PDP that enables use a "322" scalability, and the concept of *Technology Readiness Level* studied by Brady and Nightingale in the NASA Mars Pathfinder case included in Eppinger-Browning product architectures design structure matrix (DSM) examples [6].

- **Styling Iterations (SI):** Dependent variable that indicates the number of eSCRs that the final Studio surface belonging to the headlamps system had to undergo before its engineering design was frozen. Each eSCR implies an iteration in the surface of headlamps systems that is reflected in the 3D CAD data associated. SI is a variable that has number of eSCRs as unit.

- **Styling Iterations Time (SIT):** Dependent variable that denotes the average time duration from the date an eSCR was submitted for Studio evaluation and the date this was approved. Although there is an additional time that would need to be added, in this case the date when the new Studio surface was released, the eSCR system does not have individual records of changes released. The reason is that changes are added together into a single surface released at a Studio GPDS gateway or internal release to Engineering. SIT is a variable that has days as unit.

Chapter 3.2 | Simple and Multiple Linear Regression of SL, TR, SI, and SIT Variables

Aside from number and duration between submission and approval of eSCRs as the main metrics considered to find correlations, if existent, among the independent variables SL and TR and the dependent variables SI and SIT, a total of ten vehicle programs were included for data collection.

Table 2 shows the summary of observations regarding SL, TR, SI, and SIT.

Table 2. Vehicle Programs used for Linear Regressions (Round 1)

Vehicle	Independent Variables		Dependent Variables	
	Styling Level (SL)	Tech. Readiness (TR)	Styling Iterations (SI), [eSCR]	Styling Iterations Time (SIT), [days]
MKZ-13	6	2	12	17.92
Fusion-13	6	1.5	19	24.58
Navigator-15	3	3	14	12.00
Expedition-15	3	4.5	15	9.67
Flex-13	3	5	25	22.28
MKT-13	3	5	8	32.88
F150-15	6	2.5	25	14.2
MKC-15	5	5	9	8.22
Mustang-15	5	1	18	5.61
Mustang-13	3	4	5	9.80

In regard to TR, Table 3 shows the answers of the TR questionnaire provided by the exterior lighting engineers for the vehicle programs studied. Save for question 3 in which a 0.5 was acceptable when any of High Series or Low Series catalogue of the vehicle was affected, the rest of the questions were answered with 1 and 0 values corresponding to True or False, respectively.

Table 3. TR Values of Vehicle Programs used for Linear Regressions

	Tech. Readiness (TR) Criteria	Vehicle									
		MKZ 13	Fusion 13	Navigator 15	Expedition 15	Flex 13	MKT 13	F150 15	MKC 15	Mustang 15	Mustang 13
1	Interfacing frt & rr structure is carry-over	0	0	1	1	1	1	0	0	0	1
2	Lamp attachments, locators, DVA, and SRI are carry-over	0	0	0	0	1	1	0	1	0	1
3	Low Beam & High Beam are off-the-shelf projector, carry-over reflector, or surrogate reflector size (HxWxD) dimensions & proportions	1	0.5	0	0.5	0	0	0.5	1	0.5	0
4	Optical openings for all legal functions are carry-over or surrogate size (HxWxD) dimensions & proportions	0	0	0	0	1	1	0	0	0	1
5	No New technologies or light sources	0	0	1	1	1	1	1	1	0	0
6	Signature/supplemental lighting uses known/surrogate optical design	0	0	0	1	0	0	0	1	0	0
7	No New maufacturing technology	1	1	1	1	1	1	1	1	1	1
	TR	**2**	**1.5**	**3**	**4.5**	**5**	**5**	**2.5**	**5**	**1.5**	**4**
	False = 0 / True = 1										

Figures 11 to 14 show the results of simple linear regressions for SI and SIT as a function of S and TR.

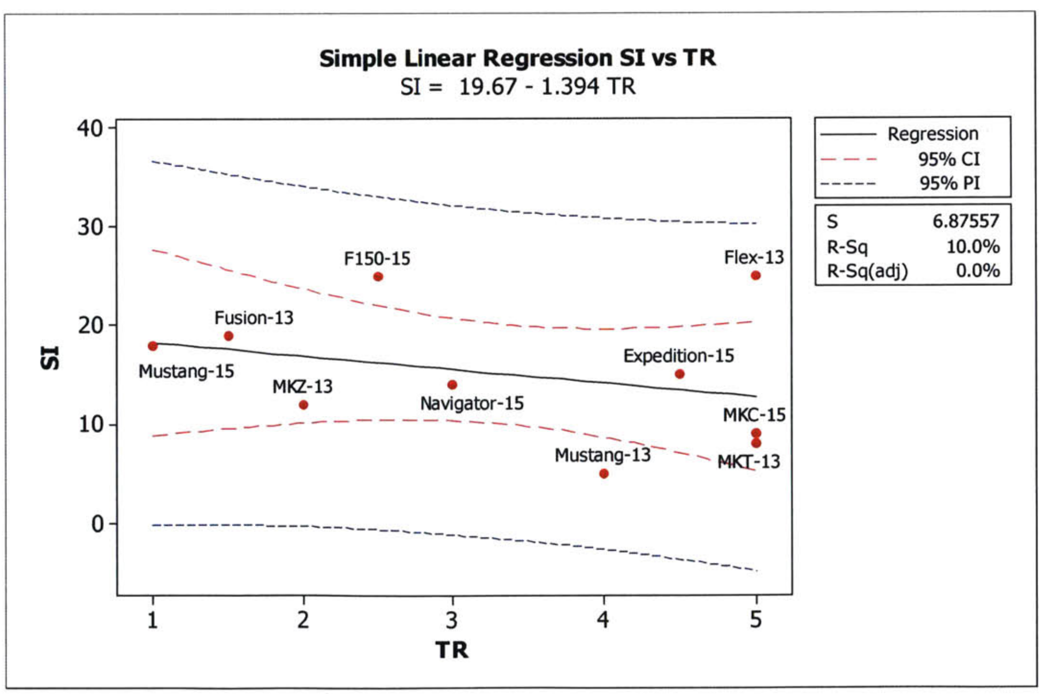


Figure 11. SI vs TR Linear Regression

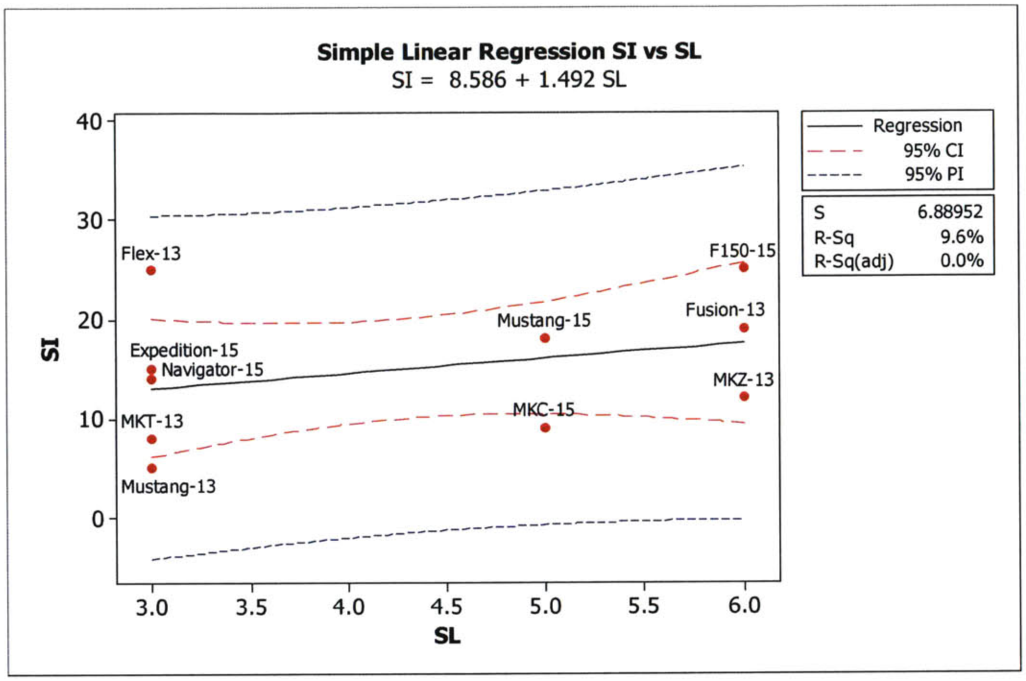


Figure 12. SI vs SL Linear Regression

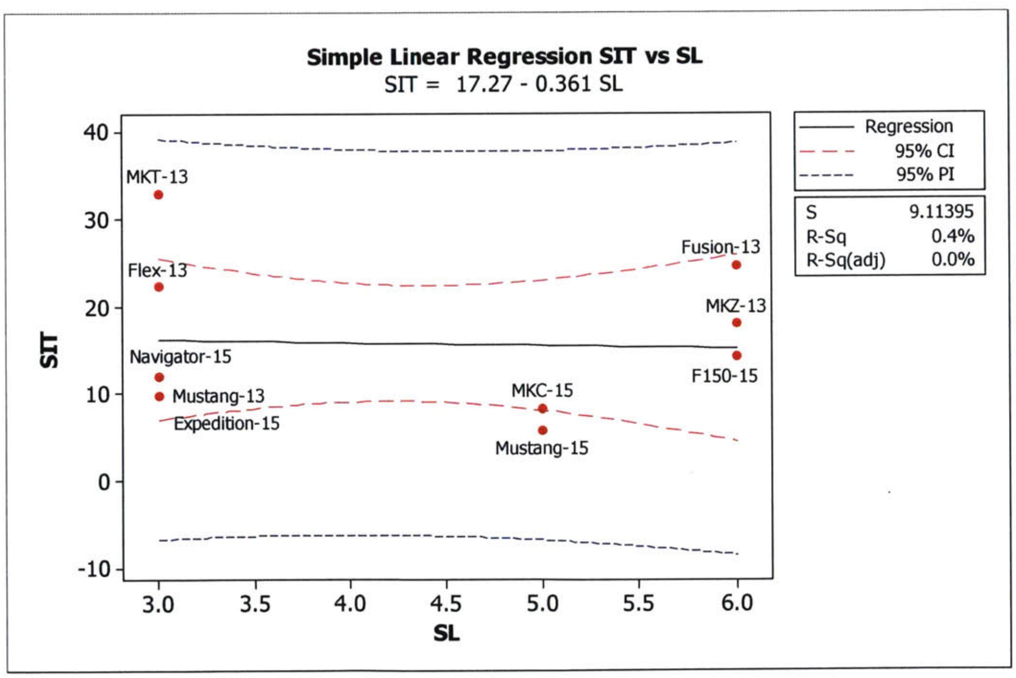


Figure 13. SIT vs SL Linear Regression

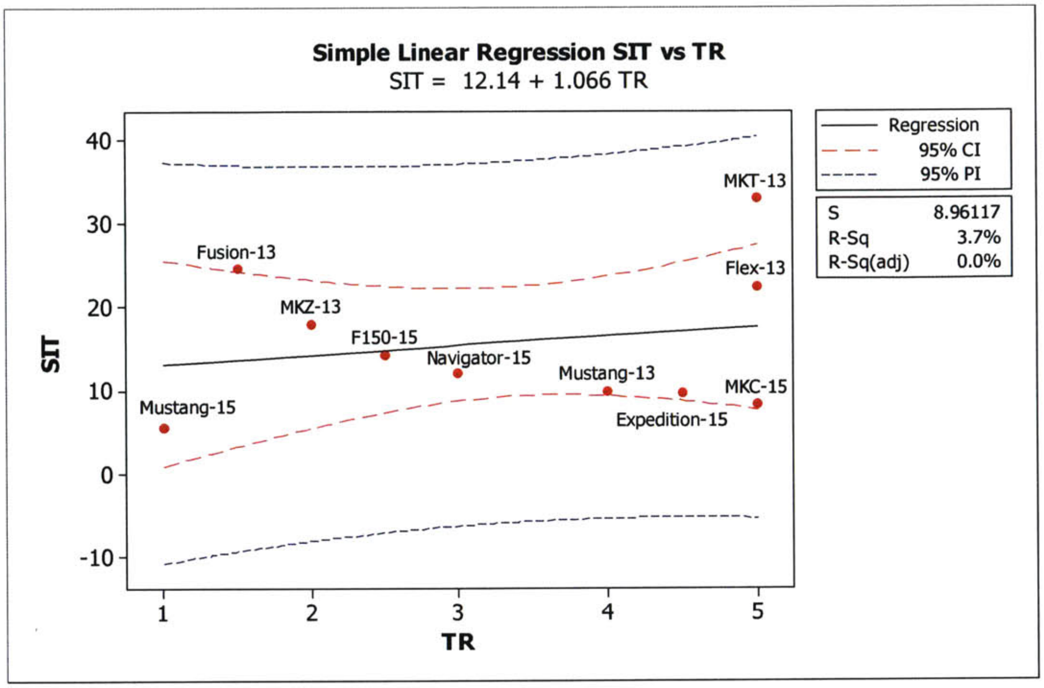


Figure 14. SIT vs TR Linear Regression

In general, simple linear regressions from Figures 11 to 14 show low values for R-Sq, situation that indicates that a linear fit does not necessarily describes the response of variables SI and SIT with respect to SL and TR, so any correlation within variables is out of the discussion as well.

Nonetheless, having a closer examination to the vehicle programs Flex 2013 and MKT 2013 that were derivatives of the same platform and Mustang 2015, it can be perceived that these vehicles had particular development performances. For example, Flex 2013 and MKT 2013 although having a SL of 3 and a TR of 5, still these vehicles together had a significant number of eSCRs and a considerable amount of days for eSCRs approval, whereas Mustang 2015 was the fastest vehicle program to approve its eSCRs despite having a SL of 5 and a TR of 1.5. So, with the intention to gather more details about these cases, it was decided to have an additional discussion with the engineers involved.

Concerning Flex 2013 and MK 2013, three basic factors provoked delays in approval of eSCRs, these were changes in Studio chromed surfaces to meet SRI craftsmanship attribute requirements, compatibility challenges with surrounding interfaces, and late addition of Adaptive Cruise Control (ACC) module that required redesign of Studio surfaces. It is interesting to point out that two out of three factors are related to TR criteria. In regard to Mustang 2015, it is worth mentioning that although its TR had a value of 1.5, this was able to incorporate a carry-over projector for the high-series model.

Regarding Flex 2013, MKT 2013, and Mustang 2015 as particular product development cases, a second simple linear regression considering the vehicles shown in Table 4 was carried out to find any correlation between among the responses of SI and SIT and the predictors SL and TR.

Table 4. Vehicle Programs used for Linear Regressions (Round 2)

Vehicle	Independent Variables		Dependent Variables	
	Styling Level (SL)	Tech. Readiness (TR)	Styling Iterations (SI), [eSCR]	Styling Iterations Time (SIT), [days]
MKZ-13	6	2	12	17.92
Fusion-13	6	1.5	19	24.58
Navigator-15	3	3	14	12.00
Expedition-15	3	4.5	15	9.67
F150-15	6	2.5	25	14.2
MKC-15	5	5	9	8.22
Mustang-13	3	4	5	9.80

Figures 15 to 18 show the second round of results of simple linear regressions for SI and SIT as a function of SL and TR.

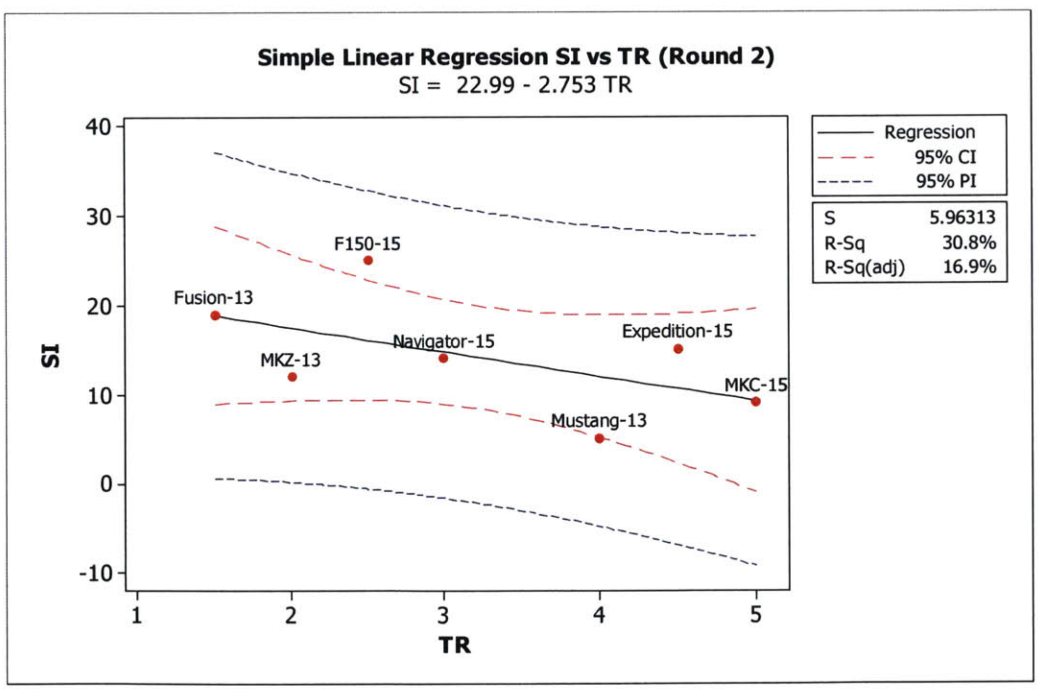


Figure 15. SI vs TR Linear Regression (2)

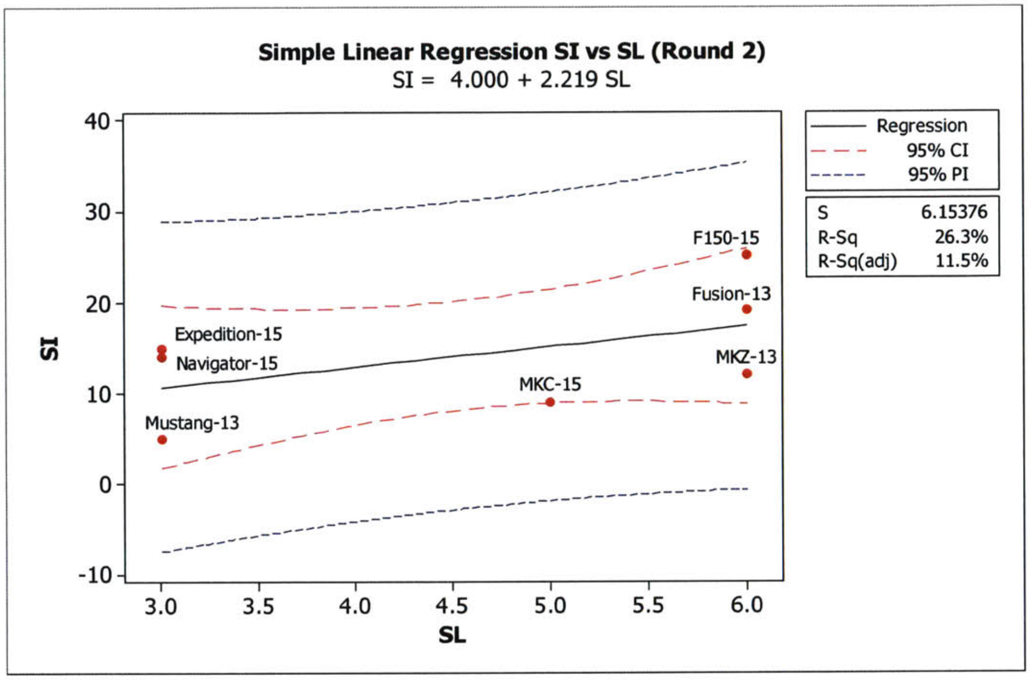


Figure 16. SI vs SL Linear Regression (2)

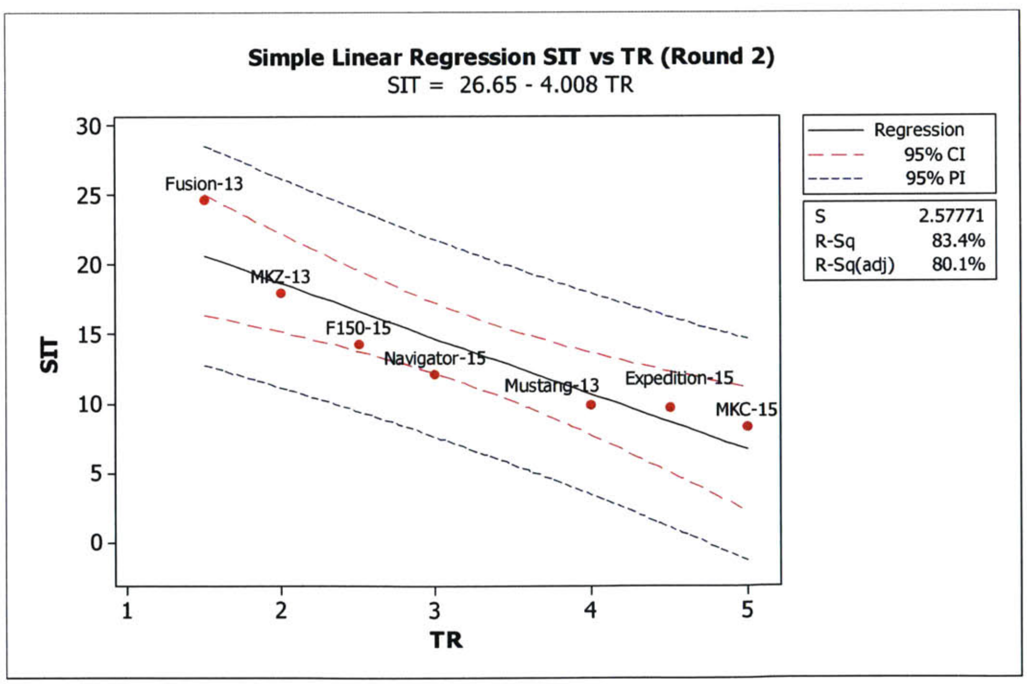


Figure 17. SIT vs TR Linear Regression (2)

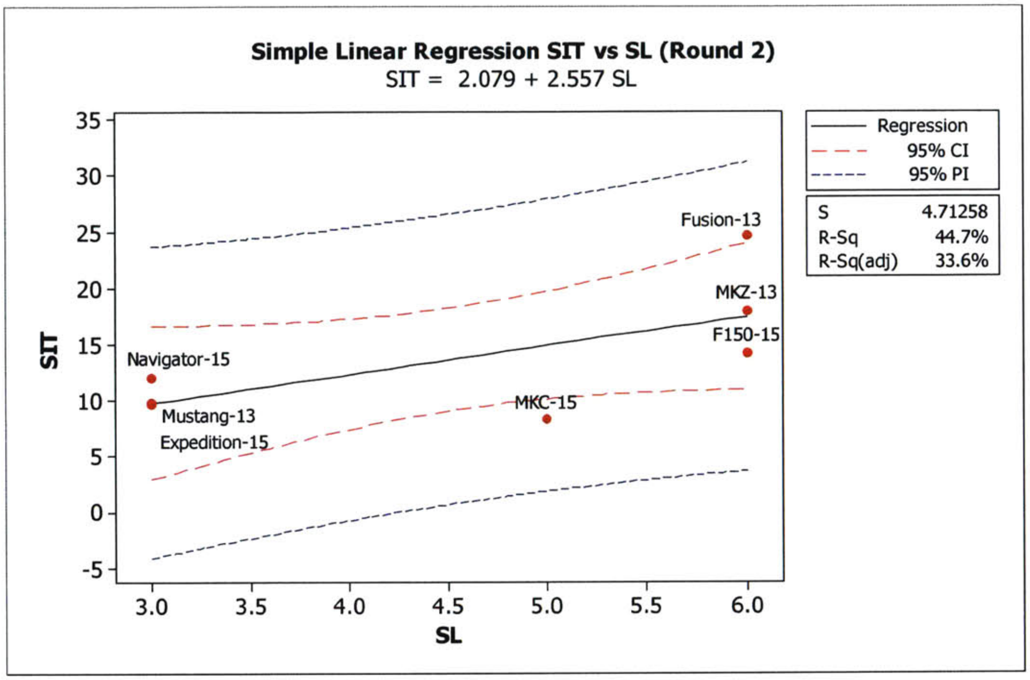


Figure 18. SIT vs SL Linear Regression (2)

After a second round of simple linear regressions, although all models exhibited an improvement in values of R-Sq these were still low with the exception of SIT and TR that clearly indicate a correlation given that its R-Sq value is 83.4%.

In view of results above, it is pertinent to inquire whether any correlation exists between each dependent variable SI and SIT when both independent variables SL and TR occur simultaneously. For doing so, a multiple linear regression was conducted.

Table 5 shows the values of multiple linear regressions for responses of SI and SIT. Such results reveal that variable SI has a low correlation with SL and TR as R-Sq has a value of 35.5% whereas p-value of both SL and TR resulted to be greater than 0.01 or 0.05 significance levels α. In regard to SIT response, this has a strong correlation with TR given the p-value of 0.029; nonetheless, its correlation with SL is low as indicated by the p-value of 0.52. The multiple linear regression equation for SIT reveals an acceptable R-Sq value of 85.3%.

Table 5. SI and SIT Multiple Linear Regression Models

SI vs SL, TR				
SI = 14.8 + 1.19 SL - 1.91 TR				
Predictor	Coef	SE Coef	T	P
Constant	14.83	16.56	0.9	0.421
SL	1.193	2.204	0.54	0.617
TR	-1.912	2.528	-0.76	0.492
S = 6.43540 R-Sq = 35.5% R-Sq(adj) = 3.3%				

SIT vs SL, TR				
SIT = 22.2 + 0.655 SL - 3.55 TR				
Predictor	Coef	SE Coef	T	P
Constant	22.17	6.995	3.17	0.034
SL	0.6552	0.9312	0.7	0.52
TR	-3.545	1.068	-3.32	0.029
S = 2.71863 R-Sq = 85.3% R-Sq(adj) = 77.9%				

Table 6 compares SIT response observations (red) from data collection with values (blue) from multiple linear regression equation that has the following expression according to Table 5:

$$SIT = 22.2 + 0.655 * SL - 3.55 * TR$$

Table 6. SIT Data vs Multiple Linear Regression Model Values Comparison

Vehicle	Independent Variables		Dependent Variables (Data vs Model)	
	Styling Level (SL)	Tech. Readiness (TR)	Styling Iterations Time (SIT), [days]	Styling Iterations Time (SIT), [days]
MKZ-13	6	2	17.92	19.03
Fusion-13	6	1.5	24.58	20.81
Navigator-15	3	3	12.00	13.52
Expedition-15	3	4.5	9.67	8.19
F150-15	6	2.5	14.20	17.26
MKC-15	5	5	8.22	7.73
Mustang-13	3	4	9.80	9.97

Figures 18 and 19 show a contour plot and a surface plot, respectively, with the intention to have a graphical insight regarding the response of SIT with respect to predictors SL and TR.

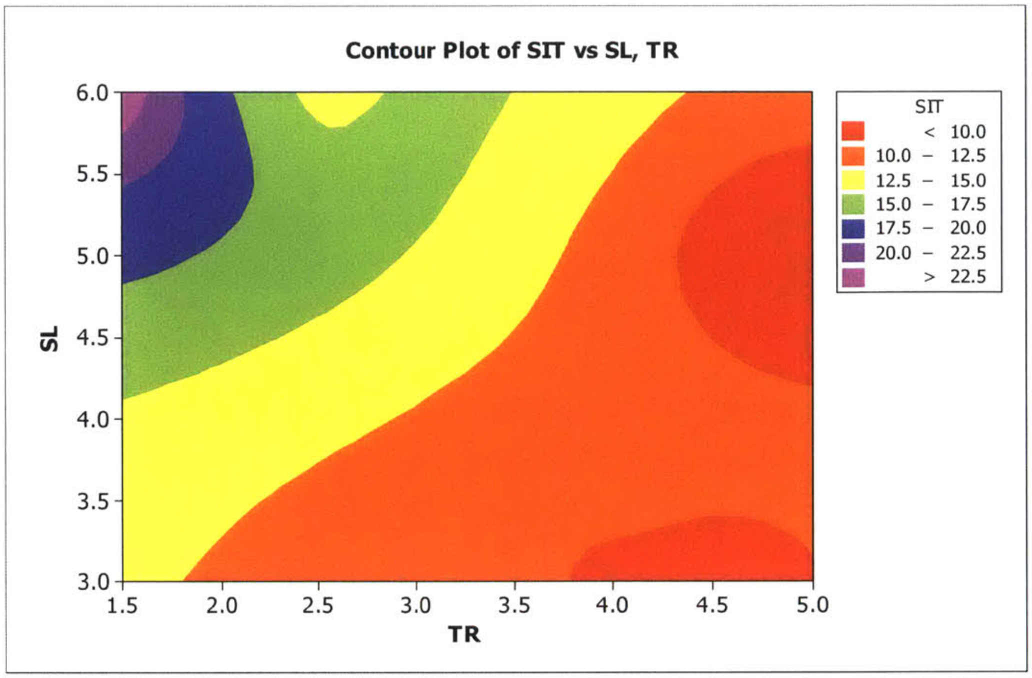


Figure 19. SIT Multiple Linear Regression Model Contour Plot

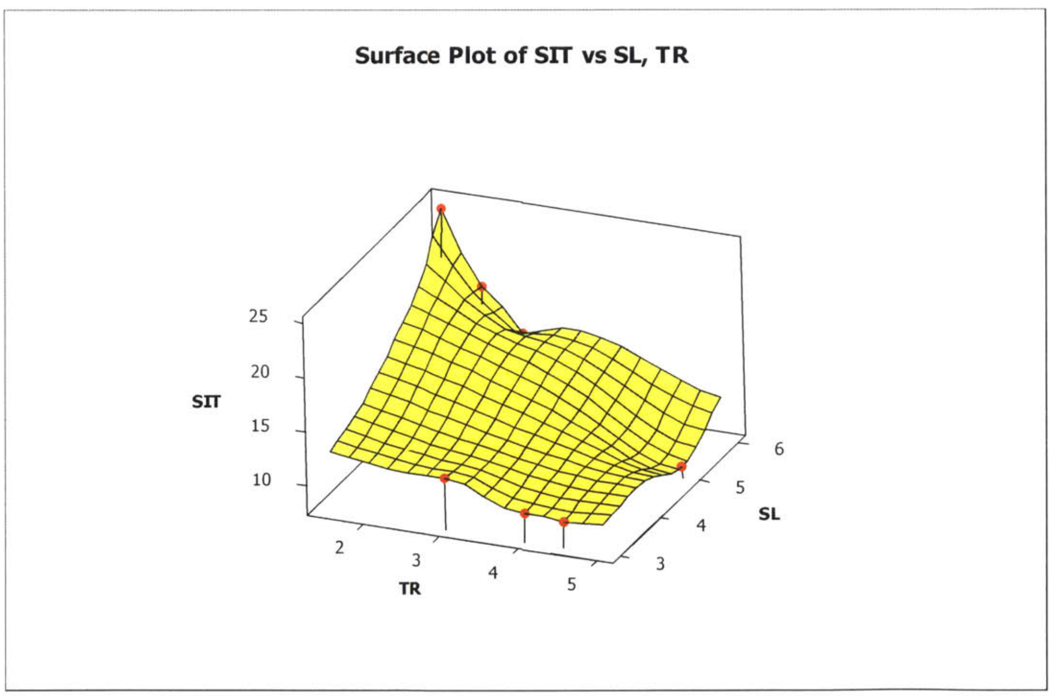


Figure 20. SIT Multiple Linear Regression Model Surface Plot

Considering SIT multiple regression model, Table 7 populates SIT response for different combinations of SL and TR factors. It is worth mentioning that contour plot shown in Figure 19 and Table 7 complement each other.

Table 7. SIT response to SL and TR values

SIT ↘ [days]		TR →												
		1	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
SL ↓	**6**	22.58	20.81	19.03	17.26	15.48	13.71	11.93	10.16	8.38	6.61	4.83	3.06	1.28
	5	21.93	20.15	18.38	16.60	14.83	13.05	11.28	9.50	7.73	5.95	4.18	2.40	0.63
	4	21.27	19.50	17.72	15.95	14.17	12.40	10.62	8.85	7.07	5.30	3.52	1.75	0.00
	3	20.62	18.84	17.07	15.29	13.52	11.74	9.97	8.19	6.42	4.64	2.87	1.09	0.00

Chapter 3.3 | SIT Multiple Linear Regression Model and its Relationship to Hypothesis

Once covered linear regressions for the observations of independent SL and TR, and dependent SI and SIT variables, there is sufficient information to revisit the main hypothesis that is:

Headlamp system derivatives belonging to a common platform with different technology readiness levels will have difficulty achieving the same timing during Studio & Engineering design iterations.

About the hypothesis, it is important to highlight that system derivatives are vehicles with the same SL, technology readiness refers to TR, timing is the SIT response, and design iterations are the SI observations.

Based on the results of multiple linear regression, given the R-Sq values and p-values, it can be concluded that although SL is the main factor used to assign UP scalability for a new vehicle, it has a low contribution to time duration of surfaces design iterative process, whereas TR revealed to be a crucial factor for both derivative, and single vehicles to be developed. The relevance of derivative vehicles is that systems, such as the headlamps, are developed simultaneously with a common SL, but not necessarily an equal TR.

Thus, there is sound evidence to accept the hypothesis statement that TR, and not SL, drives timing during Studio and Engineering design iterations.

Chapter 4 | Application of OPM Decomposition and Four-Colour Theorem to Headlamps System based on hypothesis results

I observed the length of its refracted image to be many times greater than its breadth, and that the most refracted part thereof appeared violet, the least refracted red, the middle parts blue, green and yellow in order.

Isaac Newton, *Opticks, on Proposition II*

escritura del fuego sobre el jade

Octavio Paz, *Piedra de Sol*

Based on the hypothesis that TR impacts the time required to execute changes to Studio surfaces and that majority of these actions take place during the period of AA1 – FAA gateways and PA – FDJ milestones, it can be revisited the OPM decomposition of the system and provide additional analysis that could be carried out to understand relationships between behaviors and forms represented in OPD. It is worth mentioning that TR is present across complete system development and is a key factor to ensure that activities described in the headlamps PDP, the system of interest of this thesis, are completed on time.

Such as in section 2.6 of chapter 2, a design state *Ds* of headlamps is analyzed considering that the process of Bulb and Projector Location has not being accomplished, which is a deliverable that requires collaboration between Studio and Engineering and is as well a critical TR enabler as mentioned in headlamps PDP. The analysis of the OPD bipartite graph using Hall's *Marriage* theorem is complemented with the Four-Colour theorem.

Chapter 4.1 | General Definitions of Colouring Graphs and Four-Colour Theorem

The following explanations by Wilson [5], are key to understand next section analysis:

- Planar Graph: is a graph that can be drawn in a plane without having crossings, this means that no two edges have a geometric intersection except for the vertex with which these are incident.

- A graph *G* without loops is *k*-coloured if one of *k* colours can be assigned to each vertex so that adjacent vertices have different colours.

- Chromatic Number $\chi(G)$: if *G* is *k*-colourable, but is not (*k*-1), then G is *k*-chromatic, and its chromatic number is K and it is expressed as $\chi(G) = k$.

- Chromatic Function $P_G(k)$: is the number of ways of colouring the vertices of the simple graph *G*.

The Four-Colour theorem and can be enunciated as [5]:

- *<u>Theorem:</u> Every simple planar graph is 4-colourable.*

The chromatic function $P_G(k)$ of a simple graph in terms of the chromatic functions of null graphs can be stated as [5]:

- *<u>Theorem:</u> Let G be a simple graph, and let G – e and G / e be the graphs obtained from G by deleting and contracting an edge e. Then* $P_G(K) = P_{G\text{-}e}(k) - P_{G/e}(k)$.

- *<u>Theorem:</u> The chromatic function of a simple graph is a polynomial.*

The chromatic number $\chi(G)$ indicates the minimum number of colours required to colour the vertices of a graph so that each edge joins two vertices of different colour, whereas the chromatic polynomial expresses in how many ways such assignment of colours can be made.

Chapter 4.2 | Application of Chromatic Number and Polynomial and Four-Colour Theorem to OPM decomposition of Headlamps System at a hypothetical design state *Ds*

Figure 20 shows an exploded view of the components of the new Expedition 2015 vehicle headlamp system. The reason it is shown is to have a tangible image of an example of the system so far discussed and to point out that although bulb and projector location is a process and deliverable from Studio, provided that styling is required to communicate Ford DNA, it is as well a part that implies a level of TR. So this image is suitable to have a context of the parts that need to be engineered, designed by Studio, purchased by Ford commercial department, and manufactured by the supplier, just to mention a few activities occurring during the system development.

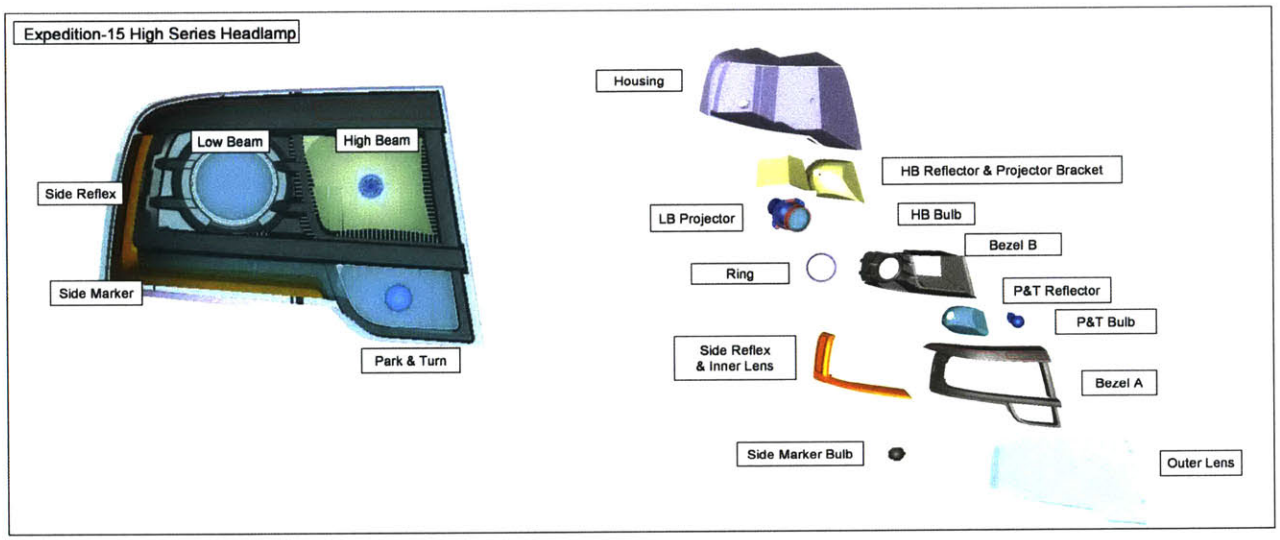


Figure 21. Expedition-15 Headlamps System's Architecture

With the intention of resuming the analysis of section 2.6 where it was pointed out that complete matching between forms and behaviors, or processes and objects, could be lost at a given hypothetical design state *Ds,* and reflected in the OPD of the system, as a consequence of having delays during Studio and Engineering activities due to an element or activity related to technology readiness. In addition, based on the hypothesis insight that TR does have an effect on the time to carry out activities such as design and styling, it is necessary to know how processes, which are delayed at a design state *Ds*, can be assigned to categories or work streams in order to better address them.

Figure 21 shows the OPM decomposition so far studied at the point where it represents absence of complete matching, from a Hall's *Marriage* theorem perspective, a situation that attempts to communicate that because of delayed technology readiness activities, objects or subsystems of the system's architecture might not even have a the appropriate process required for its completion at a given design state *Ds*. Now considering the behaviors or processes highlighted in red, these are activities that cannot coexist at the same Ds given that a delay has occurred. So a way to address this situation is to know what processes could be assigned to a work stream that could turn around the delayed situation.

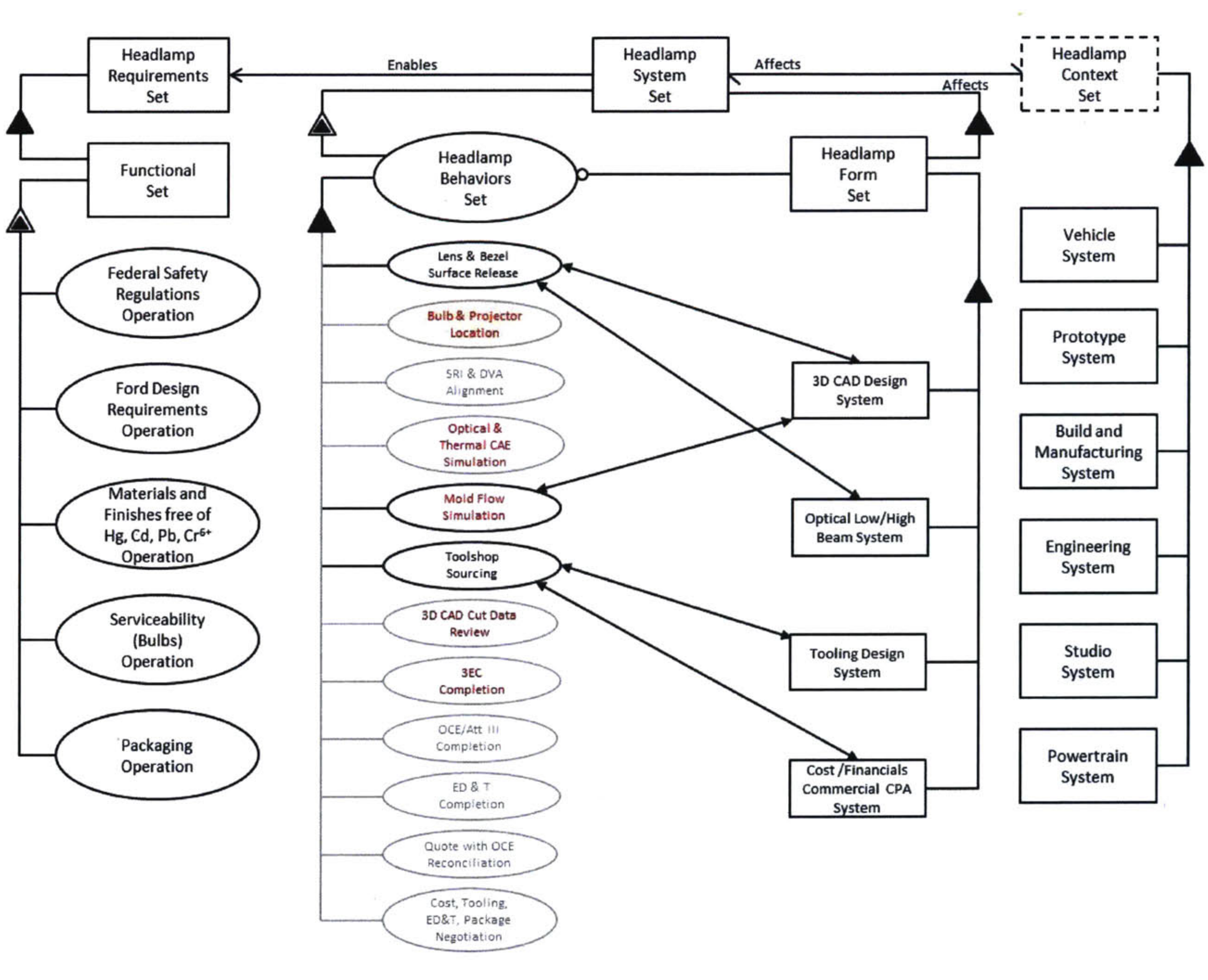


Figure 22. Processes delayed in Headlamps OPM

Table 8 shows the processes delayed from OPD of OPM. In this case, a 1 means that the process cannot coexist whereas a 0 allows to have both processes to continue being developed in parallel.

Table 8. Processes delayed in Headlamps OPM (Coexistence Condition)

OPD Process		a	b	c	d	f
Bulb & Projector Location	**a**	0	1	1	1	1
Optical & Thermal CAE Simulation	**b**	1	0	0	1	1
3EC Completion	**c**	1	0	0	1	0
3D CAD Cut Data Review	**d**	1	1	1	0	1
Mold Flow Simulation	**f**	1	1	0	1	0

Figure 23 represents the application of the Four-Colour theorem for the resulting simple and planar graph from the coexistence condition of delayed processes because of technology readiness. The result can be interpreted understanding that a work stream is represented with a colour, so in this case there are four work streams that either isolate the delayed processes and group them whenever it was possible according to the coexistence condition shown in Table 8.

It is worth clarifying that the coexistence condition is based on exterior lighting PDP and GPDS cadence and processes. Moreover, as can be appreciated, an activity or process that is related to Studio work such as the Bulb and Projector location, and that requires an assessment of its TR, if delayed has impact on other activities like the Third Engineering Concept (3EC) that are documents that detail what is the content of the part to be delivered by the supplier. These documents are part of the Commercial system during the progress of the headlamp system, so its completion on time is critical to ensure a successful development of the product.

In regard to the chromatic number $\chi(G)$ this is 4 whereas the chromatic polynomial $P_G(K)$ is shown as well in Figure 23. Although the chromatic polynomial represents the number of ways to assign, in this case, work streams to the processes and in real life as long as one way has been identified to address delayed processes, it is relevant to consider it provided simple and planar graphs are easier to visualize when deleting and contracting edges of the original graph. In addition, the condition of graphs to be planar and simple is required to apply both Four-Colour and Chromatic function theorem.

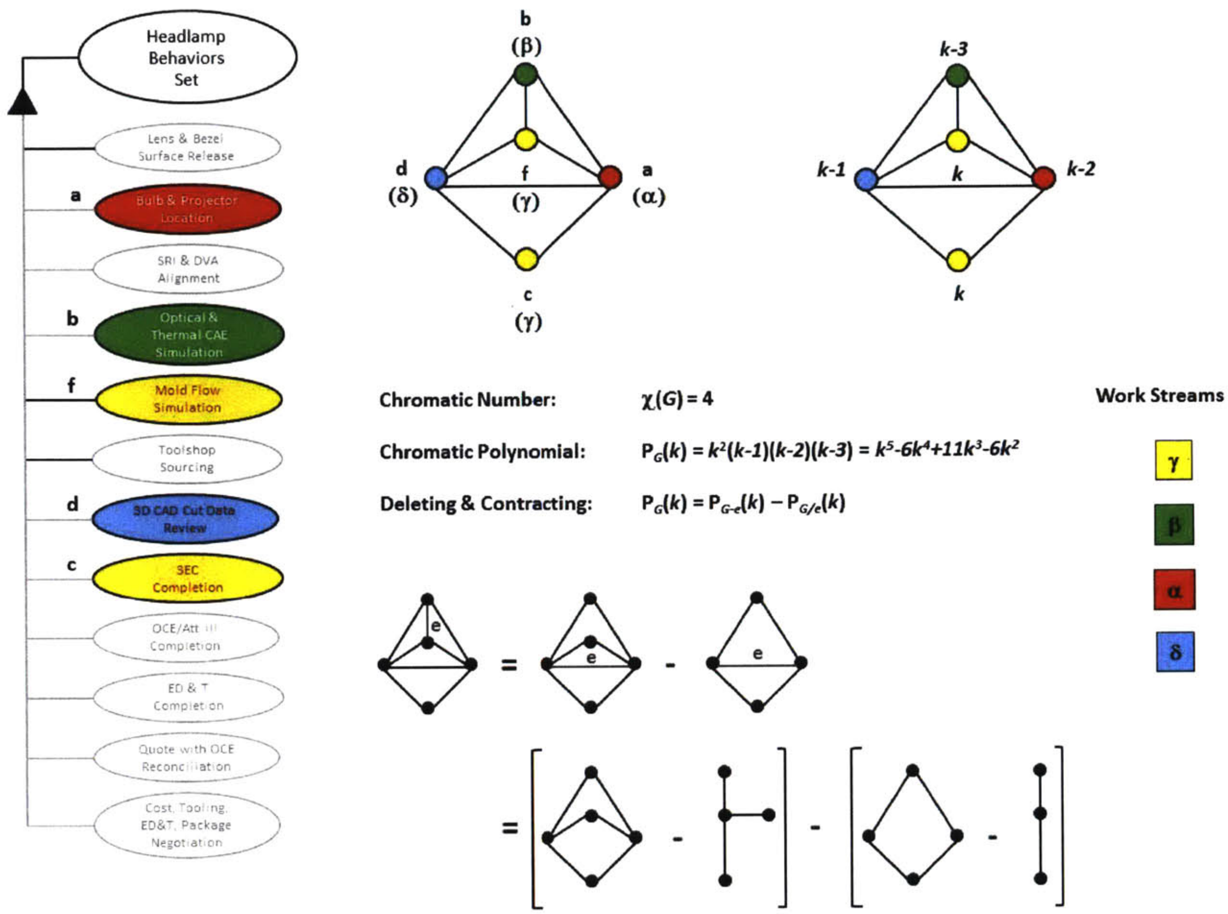


Figure 23. Application of Four-Colour Theorem to Headlamps OPM

The previous example helped to illustrate the application of Four-Colour theorem and the concepts of chromatic number and polynomial to a hypothetical design state *Ds*. Now, with the intention to answer the question mentioned in section 1.2 that refers to find a way to assign work streams to processes that have a high risk to be delayed due to technology readiness factors so to better address them, it was decided to investigate the recurrence of eSCRs during development that are shown in Figure 24.

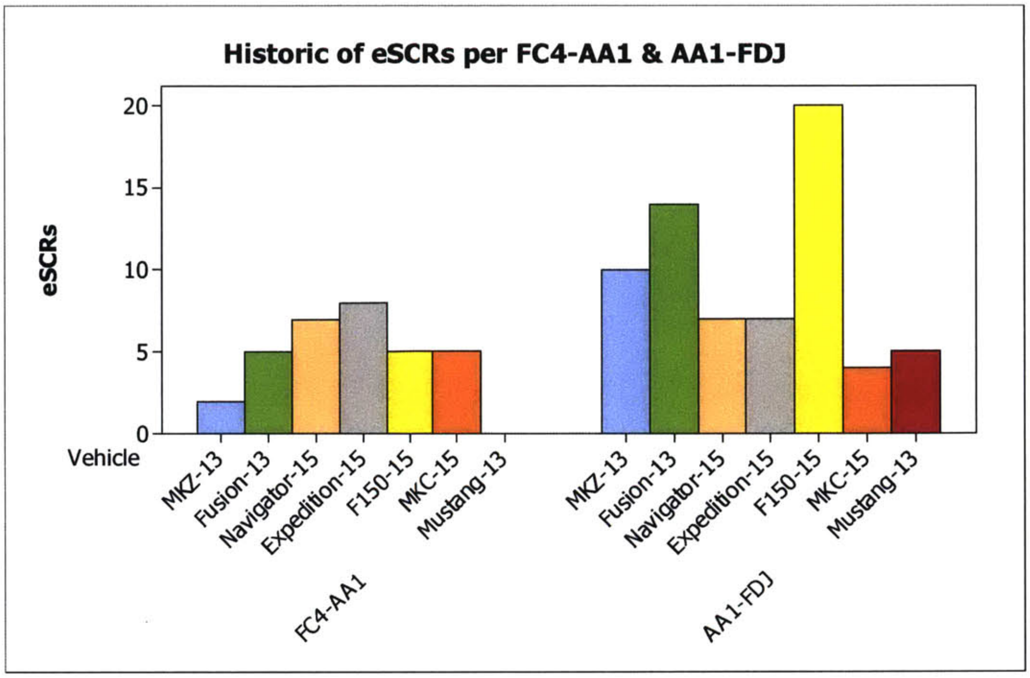


Figure 24. Recurrence of eSCRs per Vehicle Program

As indicated in Figure 24, majority of eSCRs take place in the latest Studio and Engineering gateways or milestones that would be the period AA1 to FDJ. In fact, from the 99 eSCRS accumulated from the 7 vehicle programs considered to obtain SIT multiple linear regression model, 32 fall in FC4 – AA1 period whereas 67 occur in the AA1 – FDJ interval.

Provided that TR does have an effect on timing for Studio and Engineering activities and information from Figure 24, it was then pertinent to know what processes from exterior lighting PDP have a direct connection to TR with an emphasis on FC4 – AA1 period in order to prevent delays due to TR that could affect surfaces progression during AA1 – FDJ, which is the stage that historically concentrates majority of Studio and Engineering interactions.

Table 9 identifies a number of actions from exterior lighting PDP during FC4 – AA1 period that can be mapped to TR criteria. If these activities are delayed, these actions could become non-coexistent.

Table 9. PDP activities mapping to TR during FC4-AA1

	Tech. Readiness (TR) Criteria	Exterior Lighting PDP activities
1	Interfacing frt & rr structure is carry-over	1.1 Master Sections - Feasibility Input 1.2 Design Intent 3D CAD
2	Lamp attachments, locators, DVA, and SRI are carry-over	2.1 DVA Inputs and study results 2.2 Overslam study complete
3	Low Beam & High Beam are off-the-shelf projector, carry-over reflector, or surrogate reflector size (HxWxD) dimensions & proportions	3.1 Lens and Bezel surfaces by Studio 3.2 Bulb and Projector locations frozen by Studio
4	Optical openings for all legal functions are carry-over or surrogate size (HxWxD) dimensions & proportions	4.1 Optical Openings frozen by Studio
5	No New technologies or light sources	5.1 Electrical Device Transmittals

Table 9 suggests that five sets would need to be connected in an array to which work streams or colours could be applied. In this case, given that there are multiple arrays or graphs and that Four-Colour Theorem applies to simple and planar graphs, then graphs with 5 vertices that comply with this condition, some of them explained by Wilson [5], should be the basis to organize arrays of the actions mentioned in Table 9 so to later apply a realistic colouring or assignment of work streams. For purposes of this thesis, Figure 25 only shows these graphs; by using chromatic number and polynomial concepts the minimum colours required and number of ways to colour vertices could be addressed. Taking into account Figure 25, application of chromatic number, and polynomial notions together with Four-Colour theorem used on actions mention in Table 9 attempt then to answer the question elaborated in section 1.2 that is:

How processes that have a high risk to be delayed due to technology readiness factors can be assigned to categories or work streams in order to better address them?

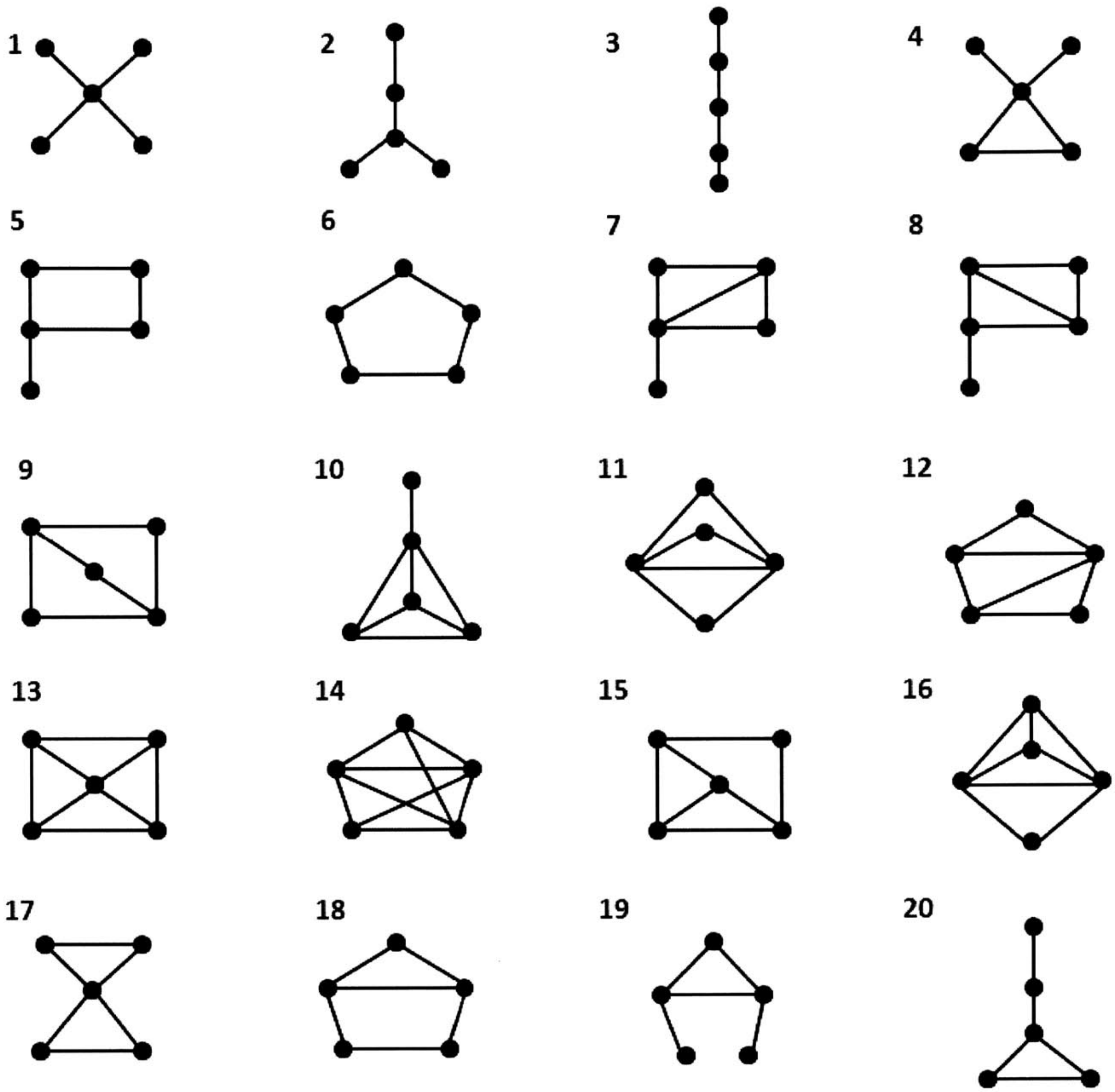


Figure 25. Simple Connected Planar Graphs with 5 Vertices

Chapter 5 | Conclusions and Final Recommendations

Transition one-dimensional movement, or placement, of objects into two-dimensional; two-dimensional to three-dimensional, etc.

Genrich Altshuller, *TRIZ – Principle 17*

En el título de las mil y una noches hay algo muy importante: la sugestión de un libro infinito. Virtualmente, lo es.

Jorge Luis Borges, *Siete Noches – Las mil y una noches*

A number of findings have been obtained from analyzing headlamp system eSCRs observations for a number of program, nonetheless, the most relevant has been the importance of technology readiness and its impact on time to carry out changes to surfaces that are critical to achieve, on the one hand, styling DNA by Studio, and on the other hand, system feasibility by Engineering. In the same way, OPM and OPD are crucial to describe the system's architecture a at a design state *Ds* that can be analyzed as well using Hall's *Marriage* and Four-Colour theorem given the hypothesis that time delays might take place during surfaces of systems design.

Chapter 5.1 | Key takeaways

The points listed below outline the most relevant results obtained and discussed in previous chapters:

- OPM hierarchical decomposition through OPD representation, together with Hall's *Marriage* and Four-Colour theorems, facilitate to understand how processes and objects of the system's architecture interact and perform at a given design state *Ds* under the influence of technology readiness TR factor.
- SL is suitable to assign an UP scalability to a new vehicle from a GPDS logic, nonetheless, is not determinant to evaluate if systems derivatives, and systems in general, will

experience difficulty achieving the same timing. It is TR the most relevant factor to consider any timing delay as it incorporates actual level of technology readiness, a finding that is supported by SIT response to linear regression models.

- SI variable, although pertinent for amount of work and eSCR metrics, is not significant to assess any timing delay during Studio and Engineering collaboration.

- Main hypothesis could be proved through SIT multiple linear regression equation, result that supports the identification of critical behaviors that either have lost match with forms or need to be isolated at a given *Ds* of the system's architecture OPD given that a timing situation has occurred.

Chapter 5.2 | Next steps at Ford PD to augment OPM – OPD – TR knowledge

The following actions have the purpose to expand on the findings discussed in previous chapters:

- Headlamps are one of the many systems of the vehicle that requires collaboration between Studio and Engineering to design the aesthetic appearance of parts while ensuring its function. Thus, the combination of TR and OPM concepts can be generalized to the rest of parts from other systems where styling and engineering need to converge. The exercise will bring insight of actual technology readiness and a better understanding of the architecture of each major system and adaptations that each system might require. For example, the material of an interior instrument panel, that could be leather or vinyl, implies to know the technology readiness in order to consider it as a real option for a vehicle that is going to be driven by a person.

- The simple and multiple linear regression models previously discussed were the result of a set of observations and a questionnaire answered by experienced headlamps systems engineers collected at FNA and FOM product development offices. Nonetheless, both the TR evaluation and OPM decomposition can be refined considering not only the FNA and FOM organizations, but also the angle of the rest of Ford PD departments around the world following GPDS and exterior lighting PDP. In the same token, it is relevant to ask the question *how are concepts of TR and OPM assimilated and integrated into* *product development by competitors?* And *how are concepts of TR and OPM assimilated and integrated into product development by other industries?*

- As previously discussed, OPM and OPD are concepts that have a relation with the discipline of graph theory. Specifically, the Four-Colour theorem was applied to graphs that are simple and planar, however, if this idea is carefully thought, it is valid to mention that an OPM and OPD representation in two dimensions was implied. In reality, OPM and OPD are an abstraction of a punctual state of the system's architecture and for visualization purposes and documentation of processes within a company such as Ford, this knowledge is communicated in a two dimensional manner. However, it is also admissible to ask *what if OPM and OPD are visualized in a three dimensional way considering the influence of TR?*

  To close this final idea, a conjecture from graph theory known as the *Erdős-Lovász-Faber conjecture* proposes that if a pair from *k* complete graphs, each having *k* vertices, share at most one vertex, the unions among graphs can be coloured with *k* colours, as shown in Figure 25 that represents an array of 4 complete graphs.

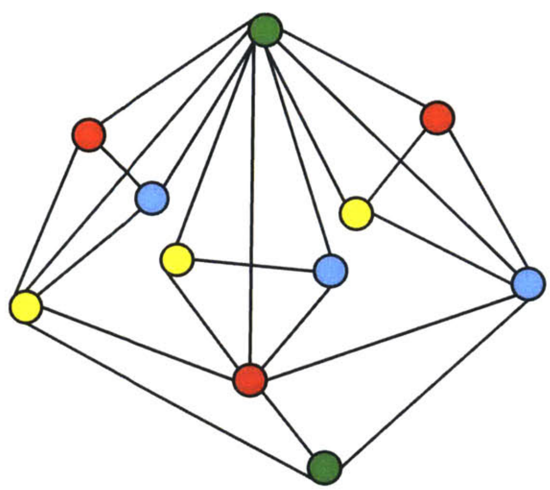


Figure 26. Erdős-Lovász-Faber conjecture

From figure above, vertices can represent those entities that are required at different work streams during a milestone and these work streams have as well have the same entities in common, so a way to relate these work streams of a milestone is to have one of the entities connecting a pair of work streams.

So, in an attempt to apply this conjecture to a TR and product development context from an OPM and OPD perspective, the final question is proposed:

Is there a way that key processes, known to be historically impacted by TR, are flexibly designed such that these could be decoupled at earlier stages from the system's progression, for deliverable completion at a certain percentage, and then reinserted to the product development cadence?

6 | Bibliography

[1] De Weck, O., Roos, D., Magee, C. L., 2011, Engineering Systems, MIT Press, Cambridge, MA.

[2] Alfaris, A., Siddiqi, A., Rizk, C., de Weck, O., Svetinovic, D., 2010, "Hierarchical Decomposition and Multidomain Formulation for the Design of Complex Sustainable Systems," ASME Journal of Mechanical Design, Vol. 132.

[3] Crawley, E., Cameron, B., 2013, *Lecture Notes for ESD.34 System Architecture*, MIT, Cambridge, MA.

[4] Dori, D., 2002, Object-Process Methodology, Springer-Verlag, Berlin.

[5] Wilson, R.J., 2010, Introduction to Graph Theory, Prentice Hall, London.

[6] Eppinger, S.D., Browning, T.R., 2012, Design Structure Methods and Applications, MIT Press, Cambridge, MA.

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