Performance Measurement in the

Product Development Process

Doctor of Engineering in Automotive Engineering

Research Project 3

PERFORMANCE PREDICTION THROUGH INFORMATION FLOW ASSESSMENT IN AUTOMOTIVE PRODUCT DEVELOPMENT

by

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ABSTRACT

This thesis incorporates project report 3 of the submission of the authors Engineering Doctorate. The intention of the project was to critically evaluate and compare methods of measuring and/or visualising information flow and to identify techniques that will lead to efficiency improvements in the automotive product development process.

The hypothesis that information flow is a leading performance indicator is verified on an automotive product development project.

Twelve techniques are evaluated for their applicability to the automotive product development process with specific focus on their relevance to an engineering service supplier.

Subsequent case study research evaluates and validates the proposed technique on a recent automotive product development project.

The research identified that the use of virtual simulation tools have increased the level of difficulty for project management teams to visualise progress.

The results show that use of the new technique would have benefitted the recent project and also demonstrate process improvement on the recovering the project.

The research is principally concerned with the automotive industry but can also have wider implications within similar industries.

PERFORMANCE PREDICTION THROUGH INFORMATION FLOW ASSESSMENT IN AUTOMOTIVE PRODUCT DEVELOPMENT

CONTENTS

1 Introduction

1.1 Research Project 3 Context

Project 2 of this research programme identified that planning and monitoring the correct rate of flow of information in the automotive Product Development (PD) could provide a key leading indicator or predictor of project success or failure. This represents a new predictive Key Performance Indicator (KPI) for the automotive PD process.

This is not currently considered in the PD process in the automotive industry where the focus has traditionally been on measuring time, cost and technical delivery.

The scope of project 3 is to evaluate methods for monitoring information flows in the PD process with the aim of developing new methods or indicators that will enable a more efficient automotive PD process.

1.2 Research Hypothesis

From the research background it is proposed that current PD processes in the automotive industry lack effectiveness and efficiency. That is, the right product for the customer is not always delivered (effectiveness) and that too many costly resources are used to deliver the result (efficiency).

Project 2 of this research programme established that performance measurement techniques in current PD processes do not measure and communicate information flows well enough.

Derived from research in project 2, a leading indicator of performance in automotive PD is the flow of project information.

Flow is a key principle of lean manufacturing and lean thinking (Womack & Jones, 2003). However, there is a gap in the knowledge in that, to date no one has demonstrated a method or technique for measuring or visualising information flow in the automotive PD process.

It is therefore proposed within this research project to evaluate and identify new methods for measuring and visualising information flow in the automotive PD process.

The new technique will provide a leading indicator of project success that will allow project management practitioners to better understand project progress and make necessary changes in resource levels to ensure timely delivery as per the original project plan, i.e. in terms of cost, timing and project scope.

1.3 Research Project 3 – Aims and Objectives

1.3.1 Aims

To identify new methods for predicting performance and employ these on an automotive PD project to demonstrate process improvement that can be realised by the profession and organisation.

1.3.2 Objectives

The original objectives 6, 7 and 8 of the research programme were:

6. To explore alternative methods of assessing performance in automotive PD.
    i. Research the use of the terms “flow” and ”information flow” in PD.
    ii. Compare processes from other industries.
7. To identify a new technique for measuring or indicating the likely success of automotive PD projects.
    i. Propose new methods indicating information flow in automotive PD.
8. To demonstrate the validity of new approach on an actual PD project in the automotive industry.

i. Evaluate the procedure with against what actually happens.

ii. Demonstrate effectiveness in order to identify area of contribution.

With the focus of project 3 now identified information flow these have evolved into:

6. To explore alternative methods of assessing performance in automotive PD.

   i. Research the use of the terms “flow” and ”information flow” in PD.

   ii. Compare processes from other industries.

7. To identify a new technique for measuring or indicating the likely success of automotive PD projects.

   i. Propose new methods indicating information flow in automotive PD.

8. To demonstrate the validity of new approach on an actual PD project in the automotive industry.

   i. Evaluate the procedure with against what actually happens.

   ii. Demonstrate effectiveness in order to identify area of contribution.

1.4 Research Project 3 – Methodology

The methods employed in project 3 to achieve aim 3 are a literature search for methods of measuring or visualising information flow followed by a case study to evaluate the chosen method that was identified and subsequently developed.

Objectives 6 and 7 were addressed by means of a literature search to explore alternative methods for performance measurement in automotive PD. This search sought to identify and develop a new approach based on information flow to improve automotive PD processes.

The assertion that monitoring information flow is a key leading indicator of project performance was first verified on an existing project. This was achieved by use of a questionnaire to survey project participants and documentary analysis of project records.

Triangulation via non-structured interviews was also employed in project 3. This allowed the participants to further expand on their questionnaire responses aswell as giving the author an opportunity to ask questions regarding his observations.

Objective 8, to demonstrate the validity of the new approach in a PD project in the automotive industry, employed a case study approach. The method identified in the literature search was further developed and refined at RLE and then deployed on a live project.

1.4.1 Research Questions

Definition of the research problem:

> How to measure/indicate/visualise information flow as a leading indicator of performance of the PD process in the global automotive industry.

The overall research questions are:

1. How can information flow be measured or visualised?
2. How can information flow be made visible and usable?
3. How can the visible information flows enable control and feedback measures to drive improvement in project performance?

1.5 Structure of the Report

Chapter 2 provides an overview of the types of information used in automotive PD process and its project management.

The significance of information flow on a real life automotive PD project is verified in chapter 3.

An exploration of information flow methods is included in chapter 4 followed by evaluation of twelve methods.

Chapter 5 describes a further investigation into the use of the chosen method and the verification its applicability to the automotive PD process.

Chapter 6 describes a case study where the new method was developed an demonstrated at RLE.

Chapter 7 discusses the implications of the new method on the automotive PD process and its business implications.

Conclusions are drawn in chapter 8 and recommendations for future work are provided in chapter 9.

2 Information in Product Development & Project Management

As described in project 2, PD processes are generally based on a formal process such as stage-gate. The research identified that the interactions within simultaneous engineering process, i.e. communication and the flow of information are key.

Browning and Ramasesh, (2007) describe how interactions in the PD process are as important as actions or tasks that are shown on a Gantt chart but are rarely considered in the process.

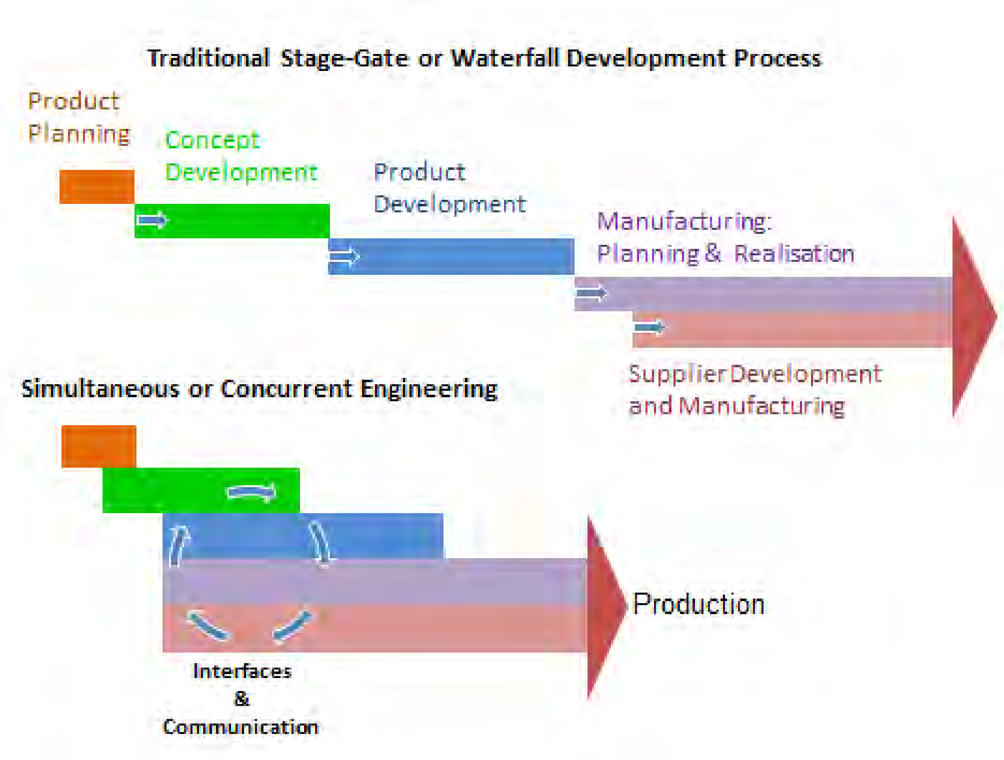


Fig. 2.1 Simultaneous Engineering Interfaces & Communication (source: RLE)

Deliverables (information) create value for the product within the PD process and thus effectiveness can be measured. The activity or department interactions are more important than the actions (Bicheno, 2008).

A leading indicator needs to be developed that provides timely feedback to a project's management team on progress toward success.

2.1 Product Development Information

Information capital (Kaplan & Norton, 2004) is a concept which states that information has intrinsic value which can be shared and leveraged within and between organisations. Various forms of information are involved in the automotive PD process.

At a project's inception, a Bill-Of-Materials (BOM), figure 2.1.1, is drawn up that lists all the parts by name, provides a part number and identifies targets for part weight and cost in terms of piece price and tooling investment. The BOM is derived from the product planning department's features required for the vehicle.

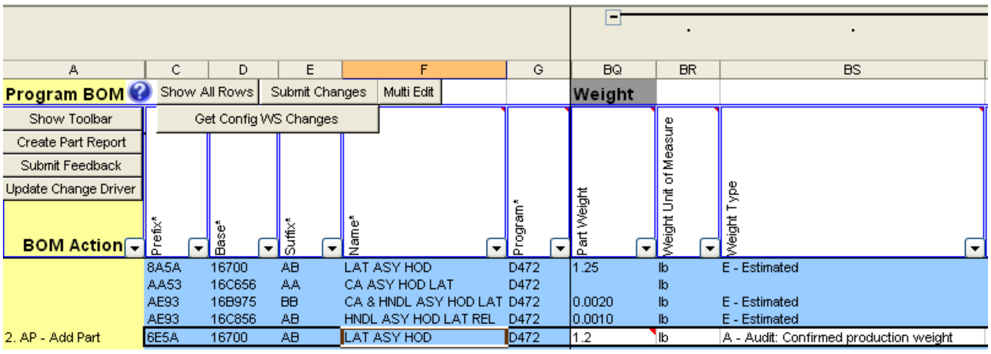


Figure 2.1.1 – Bill-of-Materials (source: RLE)

The design studio develops themes for the vehicle via 2D renderings and 3D clay models. The surfaces, figure 2.1.2, of the chosen model are developed in a computer system as Computer Aided Styling (CAS) or Computer Aided Industrial Design (CAID) models, figure 2.1.3, that are refined and handed over to the engineering functions for development into

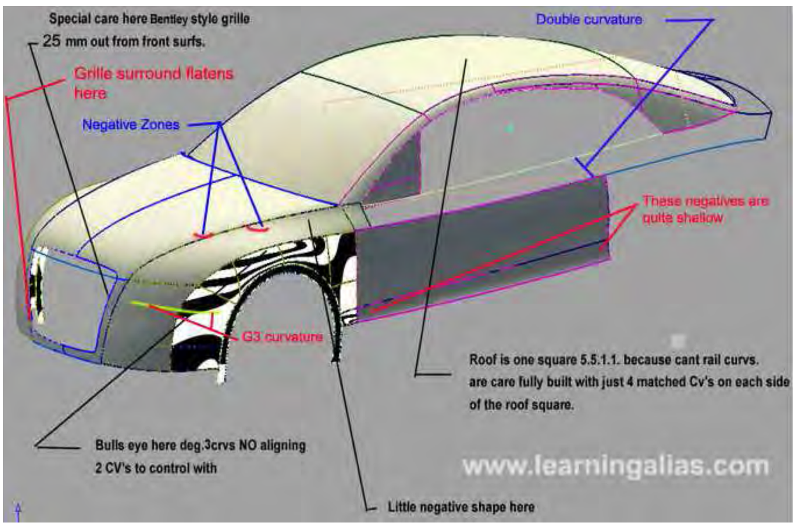


Figure 2.1.2 – Surface Model (source: RLE)

3D geometry of complete parts in a Computer Aided Design (CAD) system.

Figure 2.1.3 – Photo-realistic CAS Rendering (source: RLE)

3D CAD models, figure 2.1.4, that collectively represent the complete vehicle are developed by the engineering departments.

Figure 2.1.4 – CAD Models of a Vehicle Platform and Upper Body (source: RLE)

The CAD models are further developed into Computer Aided Engineering (CAE) models, figure 2.1.5, that are subject to virtual simulations of test conditions to verify compliance with the prescribed test criteria.

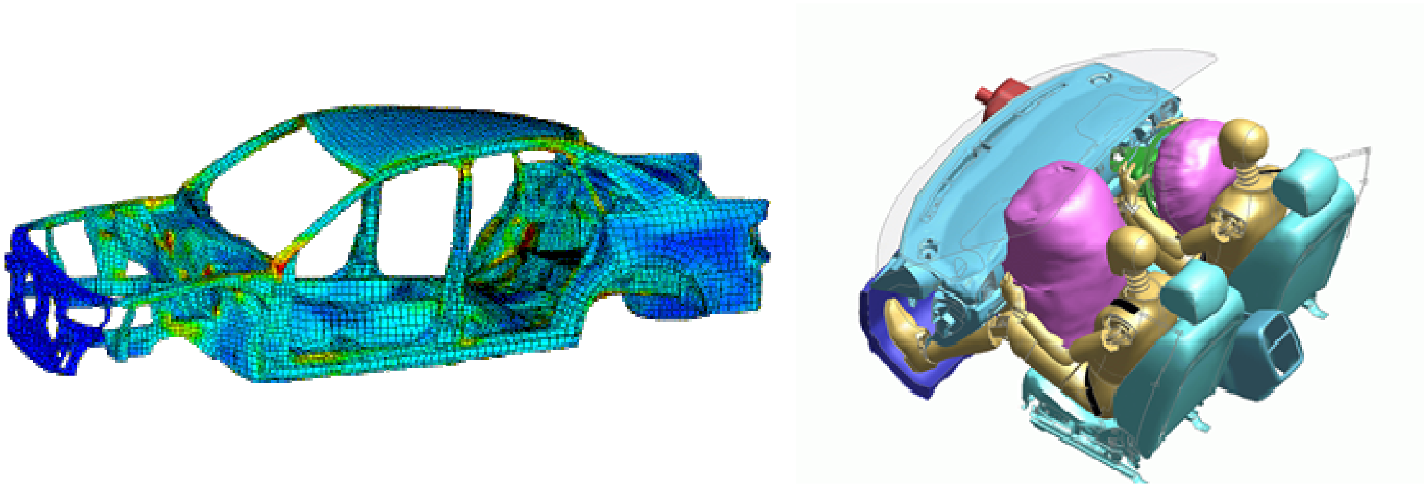


Figure 2.1.5 – CAE Models (source: RLE)

The CAD models are also utilised to develop Computer Aided Manufacturing (CAM) models, figure 2.1.6, that simulate sheet metal stamping via analysis and virtual vehicle assembly simulations.

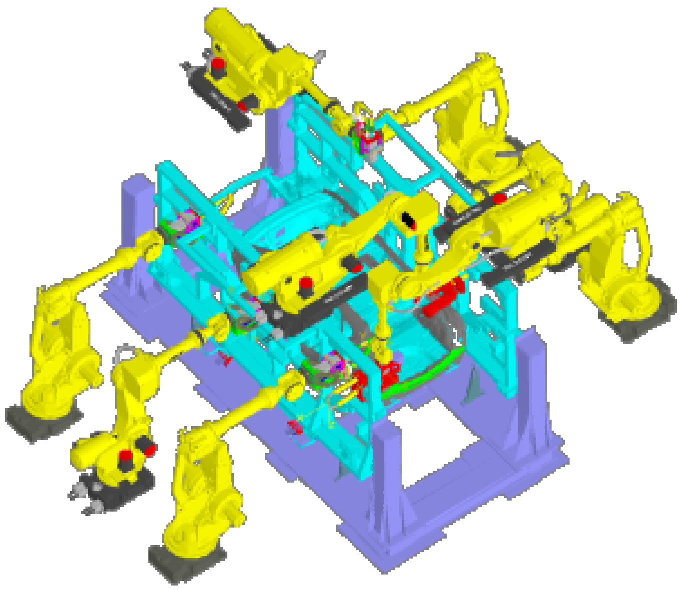


Figure 2.1.6 – Body Assembly Simulation (source: RLE)

The use of virtual prototypes developed for CAE and CAM simulations is often managed by splitting their application into a series of iterations. Figure 2.1.7 shows a Virtual Series (VS) approach with five iterations.

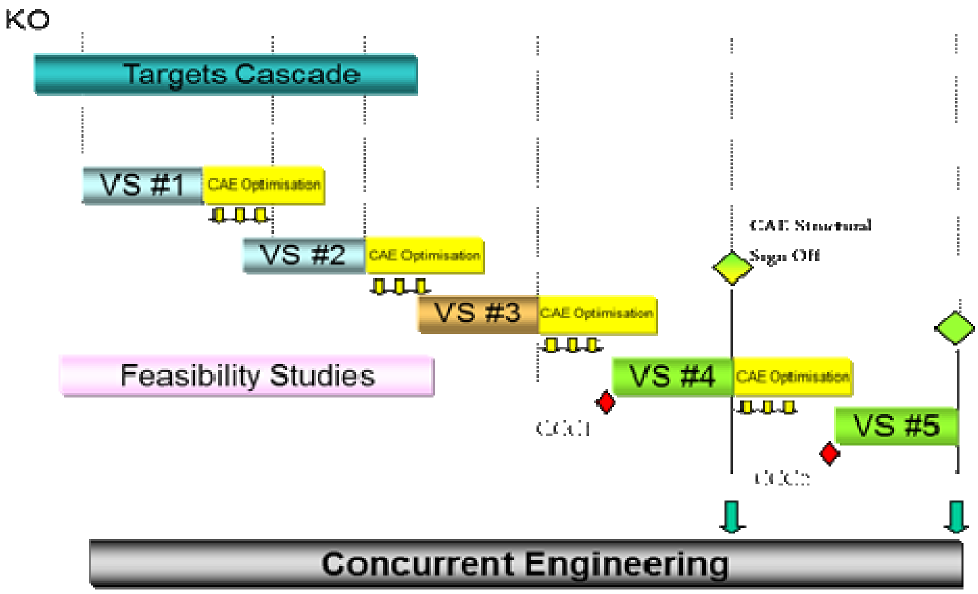


Figure 2.1.7 Virtual Series of Prototypes within Concurrent Engineering (source: RLE)

For each virtual series a detailed BOM is issued the Program Module Teams (PMTs) and a digital MRD (Materials Required Date) or Data Required Date (DRD) plan is issued in support of the prototype 'build'. This is an iterative process whereby the CAE results from each virtual series provide feedback to the master CAD model for further refinement or re-design (figure 2.1.8). In a significant re-design the BOM may need to be updated.

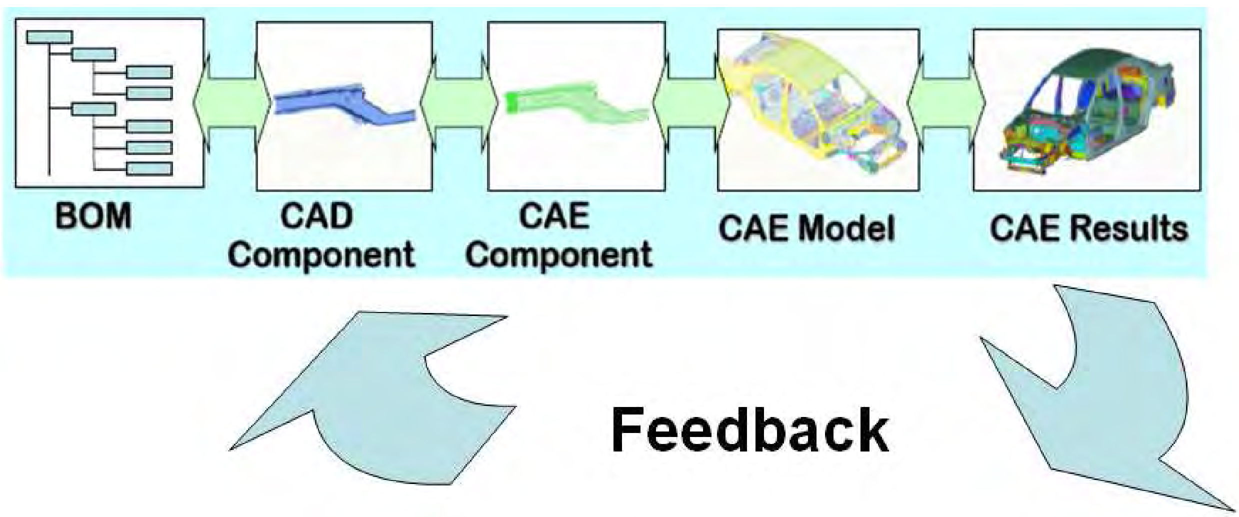


Figure 2.1.8 Information Flow in One Virtual Series Iteration (source: RLE)

Research project 2 also described the systems engineering approach V-system model for decomposition vehicle levels targets and attributes down to the into system and component levels. Figure 2.1.9 shows a series of five virtual prototypes integrated in the project timing.

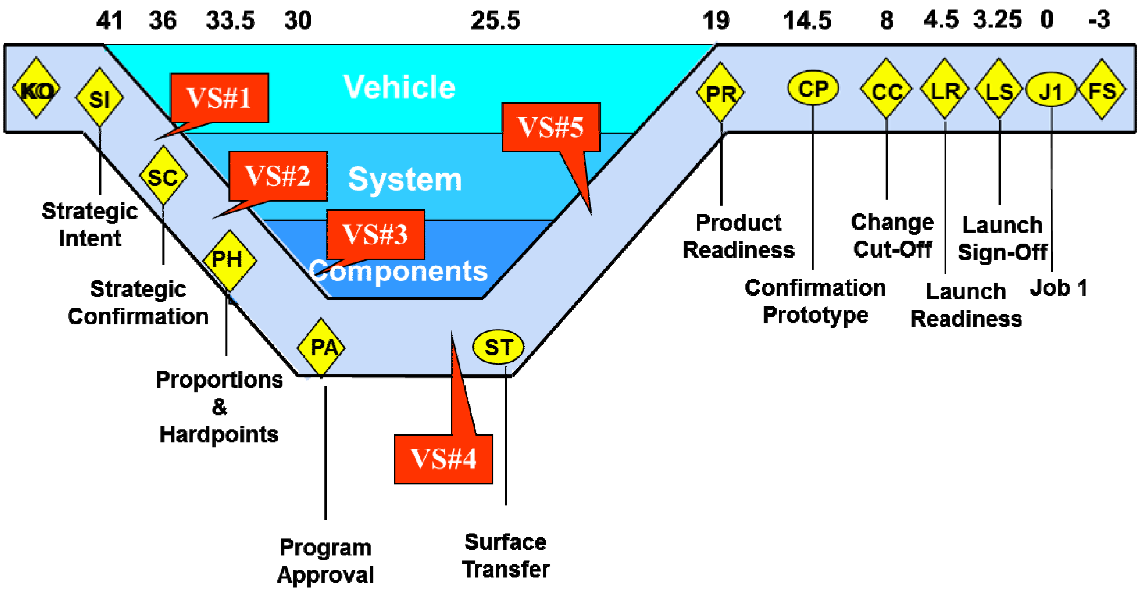


Figure 2.1.9 Virtual Prototypes and V-system Timing (source: RLE)

2.2 Project Management Information

As described in research project 2 traditional project management techniques used the triple constraint of time (schedule), cost (budget) and delivery (scope) as key performance indicators (KPIs) of success or failure. However, these do not fully convey project performance.

Additional metrics that have been developed are quality, resources and risk. Cooper and Kleinschmidt (2007) argue that human resources supply is a most significant factor in high-quality PD.

Resource levels (headcount) are budgeted for and controlled throughout projects. Research project 2 of this research programme identified that information flow needs to be planned and controlled if a project is to be successful.

2.3 Information Flow in the Project Management of Product Development

Flow of information in PD is the process of building knowledge, i.e. creating value. This is analogous to flow of components/assemblies in a factory. Flow is a key principle of lean manufacturing. Gonzales-Rivas & Larsson (2011) recognise flow as a key aspect of process performance and consider its usage and challenges in three environments:

1. Flow as a key principle of lean manufacturing.
2. Flow in the office environment.
3. Flow in the paperless (digital) office.

Gonzales-Rivas & Larsson (2011) also agree that the challenges are made more difficult the further from the factory floor you go. In the office environment, information flows tend to become more elusive and invisible, figure 2.3.1.

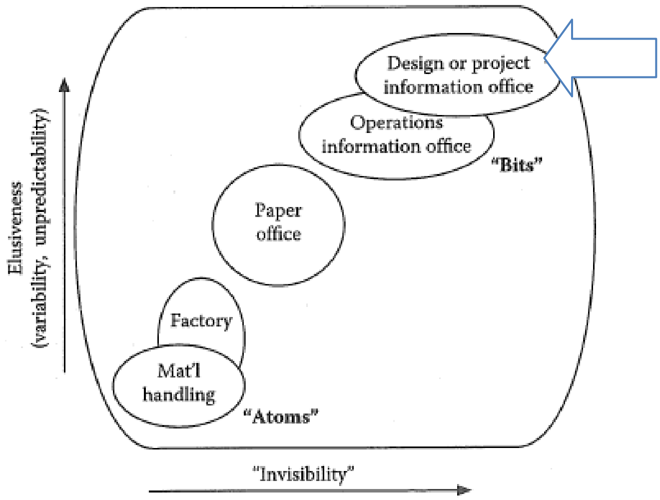


Figure 2.3.1 – Invisibility and Elusiveness of Information Flow (source: Gonzales-Rivas & Larsson, 2011)

The automotive PD process is both complex and challenging and would be at the utmost top right in figure 2.3.1. Browning and Ramasesh (2007) describe how interactions in the PD process are as important as actions or tasks that are shown on a Gantt chart but are rarely considered in the process.

The deliverable between departments is information and this creates the value in the PD process. A leading indicator needs to be developed that provides timely feedback on measures of value creation and progress toward it, i.e. process performance.

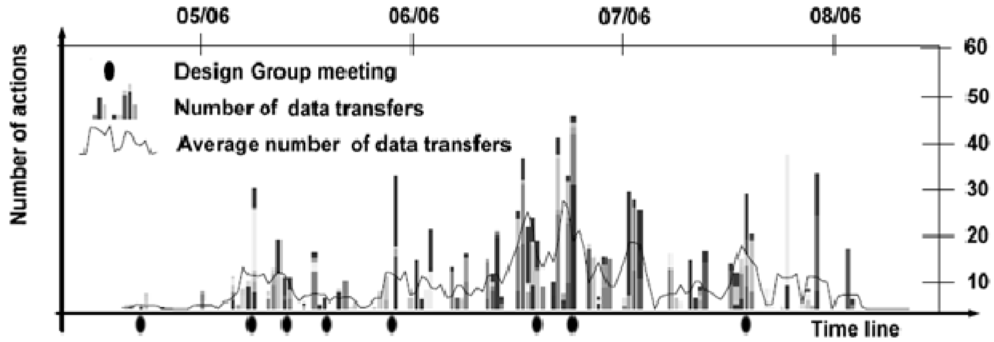
2.3.1 Evidence of Flow Consideration in Development Projects

Ballard & Howell (1997) discuss how in the construction industry, lean techniques need to be applied to avoid a mismatch between work flow and labour force plus related resources (tools, construction equipment, temporary facilities, etc.)

The importance of information flow in development projects has been recognised (Tribelsky & Sacks, 2011), figures 2.3.3 and 2.3.4. In a study of civil engineering projects they found direct correlation between objective measures of information flow and the measures of the effectiveness of design documents. However, the study used provided a retrospective outcome rather than predicting performance.

	PROJECT TYPE	DESCRIPTION OF FACILITY	BUILT AREA (m^2)	CONSTRUCTION BUDGET (MILLION $)	NUMBER OF FILE TRANSACTIONS	TIME SPAN OF TRANSACTIONS (DAYS)	NUMBER OF DESIGN FIRMS/ DISCIPLINES IN PROJECT TEAM
A	Residential buildings	A complex of 15 two-storey houses	5,000	4.5	4,870	182	14
B	Runway	A double 3,200 m long runway, 2 × 35 m wide, full structure	230,000	26.5	3,650	545	16
C	Airplane park	Aircraft parking surface	250,000	20.7	13,355	188	15
D	Sewage pumping station	A three-storey building, pumping system, air treatment facilities	320	1.4	2,457	456	12
E	Control tower	An eight-storey control tower above one office floor	800	4.2	6,515	303	16
F	Communication centre	A single-storey building	1,300	3.0	5,627	365	16
G	Infrastructure facilities	Water, waste, electricity and communication networks	NA	22.4	6,879	527	11
H	Office building	A single-storey sheltered office building	1,320	4.2	4,409	226	13
I	Workshops	A complex of three workshop buildings	2,500	2.8	3,232	430	16

Table 2.3.3 - Information Flow in a Civil Engineering Project (source: Tribelsky & Sacks, 2011)



2.3.4 - Information Flow Graph (IFG) in a Civil Engineering Project

(source: Tribelsky & Sacks, 2011)

In the automotive industry, enabling clear visualisation of information and enhancing communication have been recognised by Toyota with its Obeya (large room) concept (Tanaka, 2011), figure 2.3.5. Here cross-functional teams meet in a continuous session to clarify all project issues and agree on next steps.

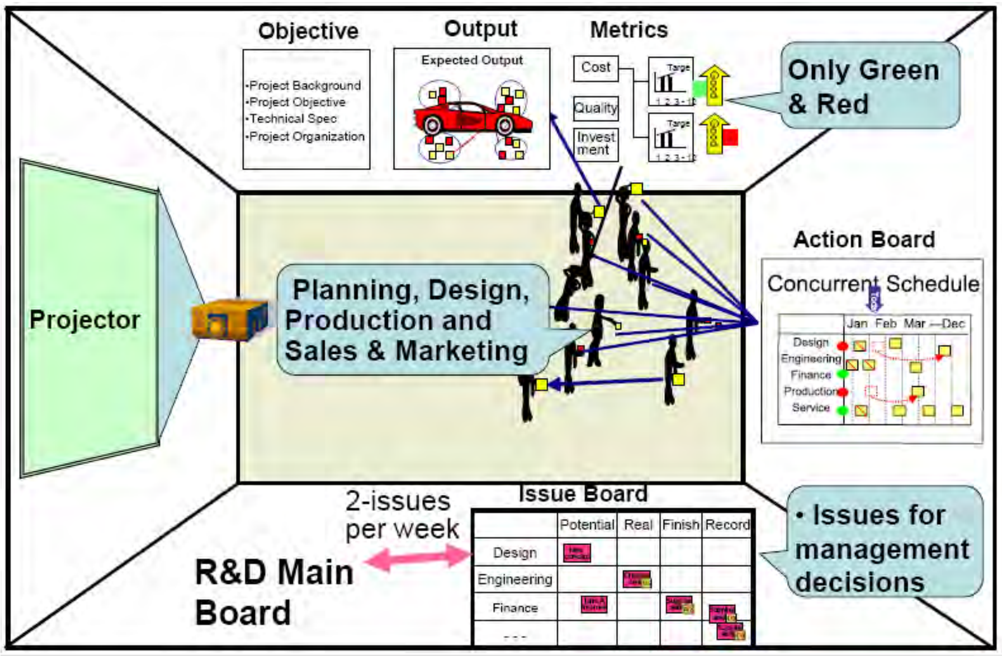


Fig. 2.3.5 - The Toyota Obeya Room Concept (source: Tanaka, 2011)

It is worth noting that the metrics are only judged as green or red, i.e. there is no yellow rating that allows objectives to be signed off as partially complete, as happens at some other OEMs.

3 Verification of Information Flow as a Key Leading Indicator in the Automotive PD Process

The identification of information flow as a key leading performance indicator of project performance in automotive PD was tested on a RLE project performed in the UK for a global OEM.

This case study followed a five component research design (Yin, 2009):

1. Study question – what is a new method of predicting performance in the automotive PD process?
2. Proposition – information flow is a predictive Key Performance Indicator (KPI).
3. Unit of analysis – the PD process is the unit of analysis.
4. Logic of linking data to the proposition – pattern matching and explanation building via qualitative and quantitative data.
5. Criteria for interpreting the findings – statistical significance but also addressing rival or alternative explanations.

3.1 Case Study Investigation and Assessment

In order to test the proposition it was necessary to select a project that was known to be failing in terms of delivery to its original plan and KPIs, e.g. timing, cost and scope or a combination of all three. A project already underway at RLE UK was identified.

RLE involvement in the project commenced in April 2011 and planned completion or Start of Production (SOP) was in late 2013. Key to this was achieving a Final Data Judgement (FDJ) milestone in early 2012, when CAD data would be released to the manufacturing department to commence tool construction. Figure 3.1.1 shows an extract from the initial project timing Gantt chart. Overall project timing is shown at A, with design studio and manufacturing feasibility activities at B and design engineering and virtual testing via CAE analysis shown at C. Figure 3.1.2 is provided to explain production timing implications linked to the iterations of the virtual series prototypes.

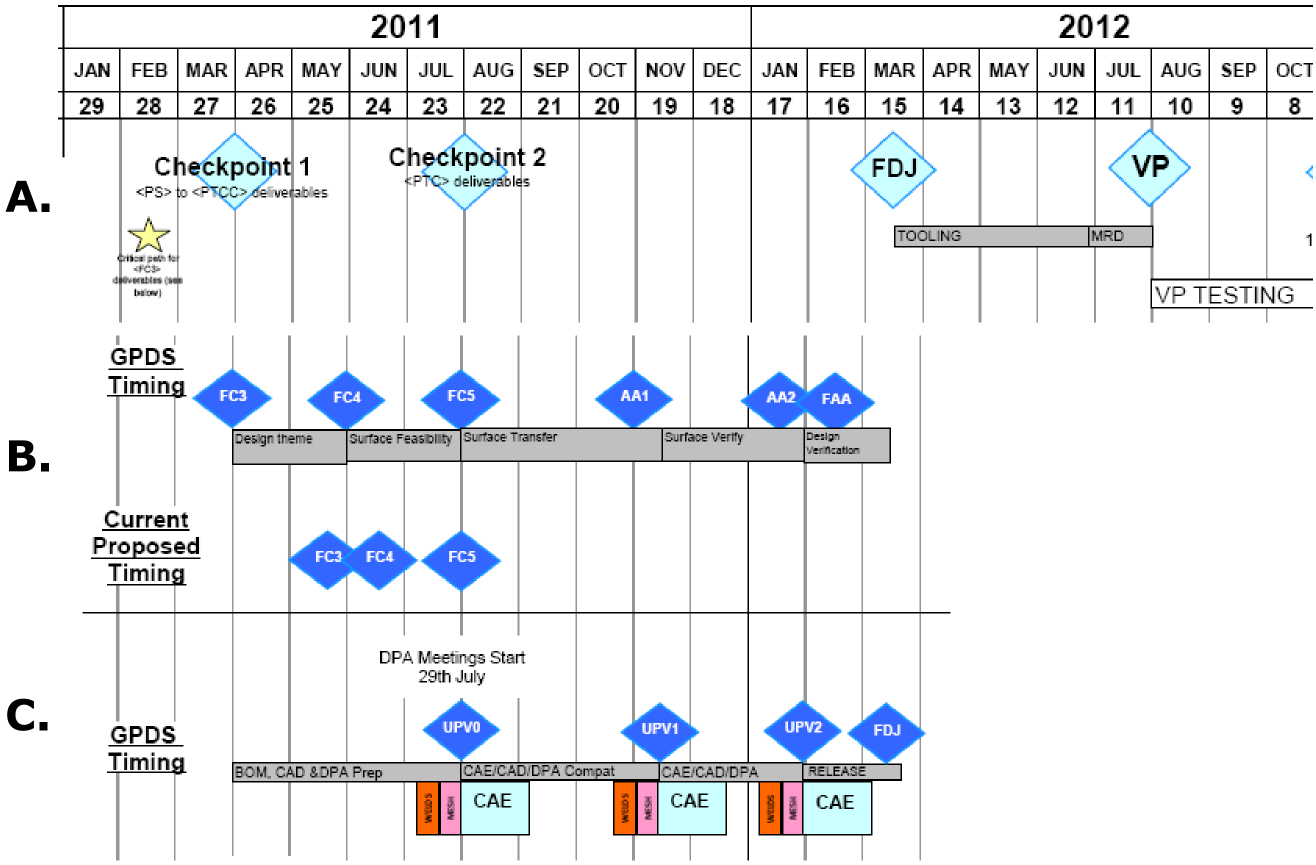


Figure 3.1.1 – Original Timing Plan Excerpt as Planned at March 2011

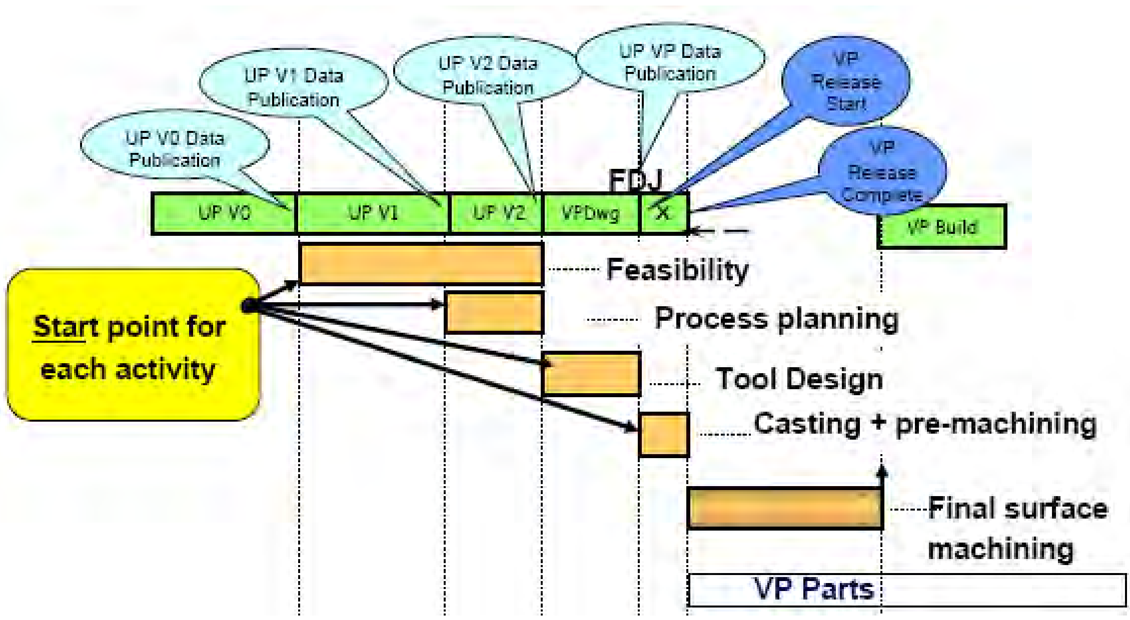


Fig. 3.1.2 Tooling Implications (source: RLE)

The key date for RLE is the FDJ gateway timed at mid-March 2012 when all design, engineering and analysis activity should be 100% complete. Initial design theme completion and Feasibility Check 4 (FC4) was planned to be complete at mid-June 2011 and FC5 complete at the end of July 2011. Appearance Approval 1 (AA1) and AA2 surface releases were timed for early November 2011 and mid-January 2012 respectively. Data from FC4, FC5, AA1 and AA2 feeds into the body engineering work-stream and enables the development of 3D CAD data and a series of three CAE Upper-body Virtual Prototypes, UPV0 – UPV2, to be complete and fully tested in the virtual environment by FDJ. RLE's responsibility in this project is for the body engineering work-stream. It is worth noting that this OEM did not provide detail of the interactions or linkages between activities on it project Gantt chart.

In reality this project timing did not happen as original planned. FC3 timed originally at the end of March 2011, and the starting point of RLE's involvement, had not been completed correctly by the OEM customer and another ESS that RLE was replacing. FC3 was delayed until late August 2011. In recognition of this delay, the FDJ gateway was retimed to 31st May 2012 with feasibility checks 4 and 5 synchronised at the end January, figure 3.1.3. AA1 and AA2 are now coincident in early March and all other activities, i.e. UPV0, UPV1 and UPV2, must still take place before FDJ.

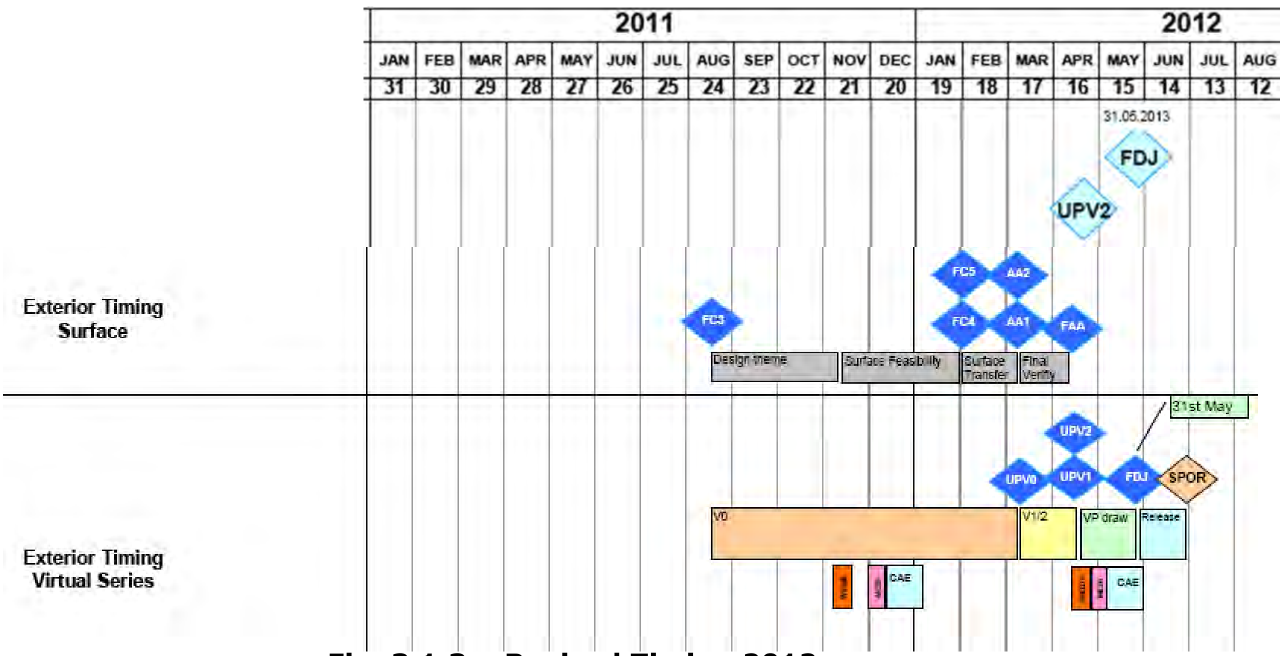


Fig. 3.1.3 – Revised Timing 2012

3.2 Proposition Testing

To test the proposition that information flow is a key predictor of PD project performance, data was collected from the RLE team on the project. The same questionnaire as used in research project 2 to assess the four projects was employed again. Of the eight experienced engineers on the project, six completed the survey.

The KPIs used on the project as identified by the respondents is shown on figure 3.2.1.

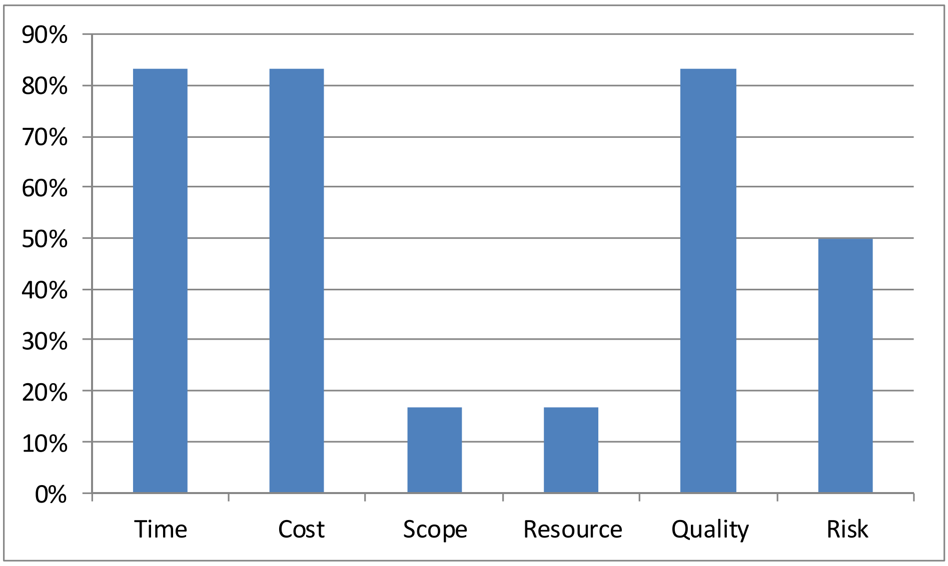


Figure 3.2.1 – Key Performance Indicators

As already acknowledged by RLE, this project was not being delivered as original planned and 100% of the respondents corroborated this in their questionnaire response. In terms of statistical significance, five other questions received 100% responses and thus had a direct correlation with the deficiency in project delivery:

1. Respondents did not attend a kick-off meeting.
2. Respondents were co-located with the majority of the project team.
3. Communication by telephone, email, CAD/Webex and face to face.
4. Information was received later than planned.
5. Information was received in small batches.

Item 4 supports the proposition that information flow is predictor of project performance, i.e. if the information does not flow as planned then project delivery will be affected. However, items 1, 2, 3 and 5 generate rival explanations to this theory. These theories were investigated via a focus group interview with the project team members. Via the focus group, items 3 and 5 were quickly dismissed as not being root causes of the project delivery failure.

However, items 1 and 2 required lengthier discussion with the group. The 100% response to item 2, on co-location, was found to reflect 100% co-location of the RLE team in one office and not with the entire project team, i.e. including the customer studio and manufacturing teams. It was established that this co-location of the RLE team was not directly related to project failure but, conversely, co-location with the customer team may have positively impacted project delivery.

Item 1, the fact that none of the team attended a project kick-off meeting, was more difficult to dismiss. The interpretation that this was a factor in the deficient project delivery was clearly expressed by the team at the focus group. Discussion with the project manager identified that there was not a definitive kick-off meeting because the team members had joined at several intervals. As previously stated the project timing did not transpire as originally planned. FC3 timed originally at the end of March 2011, and the starting point of RLE's involvement, had not been completed correctly by the OEM customer and another ESS that RLE was supplanting on the project. FC3 was delayed until late August 2011, i.e. some of the information RLE required to perform its contracted tasks was late by almost five months. This meant that the project manager had not called resources into the project as originally planned and at no point had a kick-off meeting been held. Whilst it is clear that the lack of a kick-off meeting had a detrimental effect on the project, if the meeting had taken place the project would not have been delivered as per the original plan. This is because the information to do the job was not available at the right time and this would have prevented the work being done to the original timing and cost plan.

This reflects the proposition that if information does not flow as planned then project performance will be impacted directly. Therefore, information flow is a key predictor of project performance.

3.3 Conclusions

Despite time being identified as a project KPI by over 80% of the respondents, this project was running out of control in terms of timing. This was because information was not flowing from the customer to RLE to enable tasks to be completed as per the project Gantt chart. If RLE had advanced knowledge that the information would not arrive as per the Gantt chart, resource deployment to the project could have been delayed, thus reducing the project engineers' wasted time. This would have also reduced the costs charged to the customer in this period of time.

4 Exploration and Critical Analysis of Information Flow Measurement Techniques

The automotive industry needs a tool or method that predicts project performance by measuring or visualising information flows in the PD process. This chapter considers and critically assesses methods for monitoring information flow and establishing a leading indicator of project performance.

4.1 Exploration of Information Flow Measurement Techniques

Oppenheim (2004) recognises the importance of flow in PD, but provides no measurement or visualisation technique. However, Browning (2009) does provide an overview of techniques for modelling processes, table 4.1.1, that provides some consideration of assessing flow.

In terms of information flow we can return to Gonzales-Rivas & Larsson (2011) and their recognition of flow as a key aspect of process performance and consider its usage and challenges in three environments:

1. Flow as a key principle of lean manufacturing.
2. Flow in the office environment.
3. Flow in the paperless (digital) office.

Gonzales-Rivas & Larsson (2011) provide a table, 4.1.2, that describes the practicality of applying lean techniques to the three environments listed above.

Twelve techniques were selected from tables 4.1.1 and 4.1.2 for further analysis. The criteria used in selecting the techniques were:

- Identification of inter-department interaction or linkages.
- Representation of flow of information.

View	Example References	Primary Attributes			Comments
		Process	Activity	Deliverable	
Process flowchart – Network diagram – PERT chart – Activity-on-node (AON) diagram	[IBM 1969] [Moder *et al.* 1983] [Elmaghraby 1995]	Name, Children	Name, Suppliers, Customers		Often enhanced to include additional attributes, such as Responsible Organization (via "swim lanes"), etc.
Gantt chart – Milestone chart	[Gantt 1919]	Name, Children, Milestone Events	Name, Duration, Start Time, Finish Time		Often enhanced to include additional attributes, such as Percent Complete, Process/Activity hierarchy (Parent-Children), etc.
Design Structure Matrix (DSM)	[Browning 2001]	Name, Children	Name, Suppliers, Customers, Activity Sequence Vector	Supplier, Customer(s)	Often enhanced to include additional attributes such as: Duration, Responsible Organization, Rework Probability, Rework Impact, Process/Activity hierarchy (Parent-Children), etc.
GERT diagram	[Pritsker and Happ 1966]	Name, Children	Name, Suppliers, Customers	Flow Probability	
Textual narrative	[SPC 1996, pp. 50f; Olson 2006]	Name, Narrative Description			Various activity and deliverable attributes may be embedded depending on the guidelines followed
High-level "life cycle" models – Stage-gate/ waterfall model – Spiral model – "Vee" model	[Unger and Eppinger 2002] [NASA 1995; Cooper 1994] [Boehm 2000] [Mooz and Forsberg 2006]	Name, Children, Planned Iterations, "Toll Gates"	Name, Suppliers, Customers Mode		Typically used only at a high level, to show the major phases of a large project
IDEF0 diagram	[NIST 1993; Feldmann 1998]	Name, Children	Name, Suppliers, Customers, Inputs, Outputs, Identification Number	Name, Supplier, Customer(s), Parent, Children	Distinguishes three types of inputs—data, controls, and mechanisms—and two types of outputs—data and calls
IDEF3 diagram	[Mayer *et al.* 1995]	Name, Children	Name, Suppliers, Customers	Flow Conditions	Emphasizes the synchronous or asynchronous AND, OR, or XOR flows among activities
State diagram – Event graph – Markov chain – Data flow diagram – Directed graph	[Harel 1987]	Name, Children, States[a]	Name, Suppliers, Customers	Name, Transition Conditions, Transition Probability	Activities are states; used by Petri Net and Unified Modeling Language (UML) models; project process applications require possibility of being in more than one state at a time
Activity-on-arc (AOA) diagram	[Elmaghraby 1995]	Name, Children, States	Name, Suppliers, Customers, Duration		Activities are the transitions between states; includes dummy arcs and events
CRUD Table			Name, Type of Use (for each deliverable)	Name	Often used to model database and information system architectures
Value Stream Map	[McManus 2005]	Name, Children, Cycle Time	Name, Suppliers, Customers, Cycle Time, In-Process Time	Wait Time	Recently adapted for modeling project processes; can also show additional features of process; emphasizes identifying sources of waste in processes
Stock-and-flow diagram	[Sterman 2000; Ford and Sterman 2003]	Stocks and flows of work; metrics			Does not identify discrete activities, deliverables, or precedence relationships; models completion of generic work

Table 4.1.1 - Common Views of Process Models (Browning, 2009)

Tool or Technique	*Factory Lean*	*Paper Office*	*Info Age Office*
Posters	●	◕	◔
Newsletters	◕	◑	◔
Wikis and blogs	○	◔	●
F2F kaizen meetings	●	◕	◑
Online kaizen	○	◔	●
VSM	●	◕	◔
Takt time	●	◔	◔
Pull/Kanban	●	◑	◔
APD	○	◔	●
Cumulative flow	●	●	●
Poka yoke	●	●	●
5S	●	◑	◔
SMED	●	○	○
DSM	◔	◔	●
Heijunka	●	◔	◕
Muda	●	◕	●
Mura	●	◑	●
Muri	●	◔	◕
OEE	●	○	○
Gemba	●	◑	◑
5 Whys	●	◑	◕
Jidoka	●	◔	◑
Andon	●	◔	●

Key to Symbols: the level of shading represents the degree of applicability.

Table 4.1.2 - Practical Applicability of Lean Tools

(source: Gonzales-Rivas & Larsson, 2011)

The selection of the methods and techniques listed in tables 4.1.1 and 4.1.2 provided a shortlist of twelve approaches to be assessed further:

1. Workflow charts & business process modelling.
2. Value stream mapping.
3. GERT diagram.
4. Consideration of fluid dynamics.
5. Stock-and-flow diagram.
6. Traffic light system.
7. Kanban charts.
8. Burn-up diagram / Burn-down diagram.
9. Cumulative flow diagram.
10. Earned value management.
11. IDEF0 / IDEF3.
12. Design structure matrix.

The Gantt chart was not included as it has already been demonstrated in the case study in chapter 3 of this report that this method is inadequate for consideration of departmental interactions and information flow tracking.

Workflows or work-streams with swim lanes, figure 4.1.3, are often used to model business processes, but do not identify rates of flow. Business process modelling applies logic to decisions to make some loops automatic and reduce administration tasks.

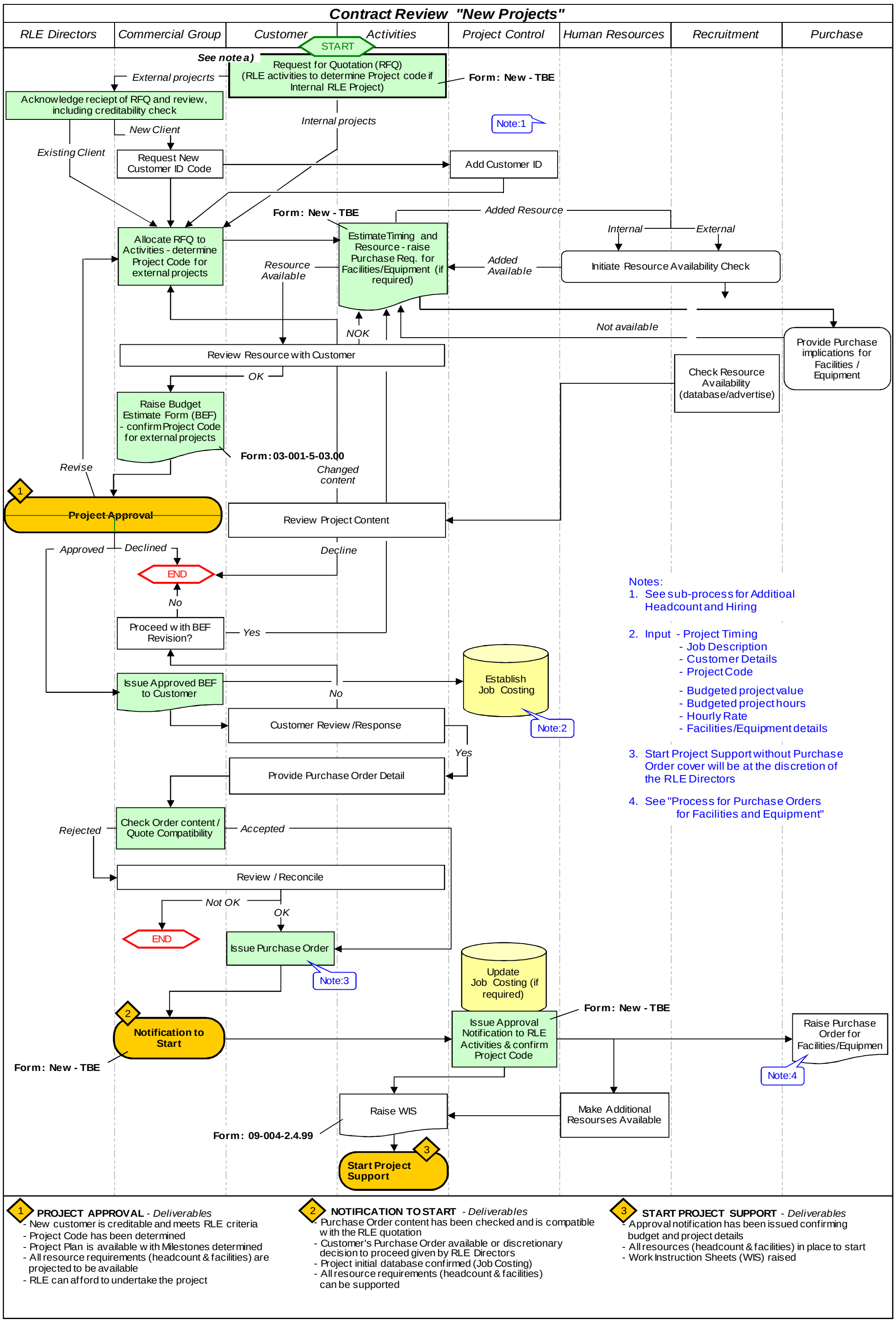


Figure 4.1.3 – Workflow Model (source: RLE)

Value stream mapping is used extensively in manufacturing but Toyota has deemed it too complex for whole product development process (Tanaka, 2011). However, the Massachusetts Institute of Technology's (MIT) Lean Aerospace Initiative (LAI) is in the process of developing a "Product Development Value Stream Mapping (PDVSM)" manual.

Graphical Evaluation and Review Technique (GERT) diagrams, an extension to PERT according to Browning (2009), provide an ability to model flow and associated loops but their dependence on complicated computer modelling renders the approach too complex for further consideration for the automotive PD process and its flow characteristics.

The theory of fluid dynamics would seem a natural source of flow measurement techniques, e.g. Reynold's Number etc. The discussion of whether information flow is laminar or turbulent in the case of simultaneous engineering flow of information would provide an interesting study.

The stock-and-flow diagram, figure 4.1.4, models activities as stock of work to be done at some rate of flow. However, it does not account for interactions between activities. What is required is a system that measures the flow at the interactions, e.g. a flow meter between activities.

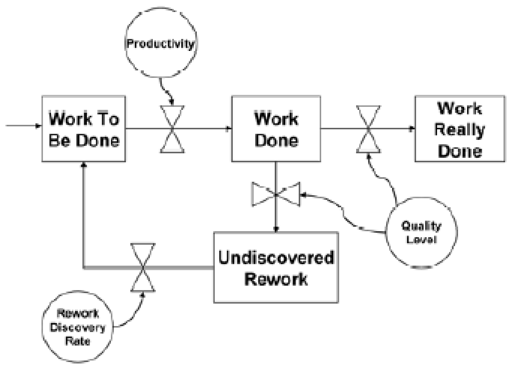


Figure 4.1.4 - Stock-and-flow diagram (Browning, 2009)

Traffic light systems, figure 4.1.5, are used by a number of OEMs to indicate the status of metrics or deliverables at a point in time, particularly at gateway reviews. However, in the author's experience these systems are unreliable as the logic used, figure 4.1.6, is often misinterpreted or simply abused by certain departments at the detriment of others.

Current MS Note: Milestones with an asterisk indicate Carry-Forward Deliverables		[illegible]	[illegible]	[illegible]	[illegible]
VG-T-80-D14	Upper Body V0 Part Setup (includes all NTEFs, Hardware, Software, Bridging and Carryover parts)	✓	✓	✓	✓
VG-T-80-D15	Upper Body V0 Variable Cost Status	✓	✓	R	✓
VG-T-80-D16	Upper Body V0 Investment (Program Supplier Tooling & Facilities) Status	✓	✓	R	✓
VG-T-80-D17	Upper Body V0 Weight Status	✓	✓	R	✓
VG-T-80-D19	Upper Body V0 Technical Design/Functional Reviews Complete	✓	✓	✓	✓
VG-T-80-D20	Upper Body V0 Qualifications from Previous Milestones/Gateways	✓	✓	N	✓
VG-T-80-D22	Upperbody New Technology Design Specifications Agreement	✓	✓	N	✓
VG-T-80-D23	Upper Body V0 DPA 2 - Craftsmanship Work Plan	✓	✓	✓	✓
VG-T-80-D24	Upper Body V0 DPA 3 - Appearance Tolerance Work Plan	✓	✓	✓	✓
VG-T-80-D25	Upper Body V0 DPA 4 - Service Work Plan	✓	✓	✓	✓
VG-T-80-D26	Upper Body V0 DPA 6 - Package/Ergonomic Work Plan	✓	✓	✓	✓
VG-T-80-D27	Upper Body V0 Quality Target Achievement Status	✓	✓	N	✓
VG-T-80-D29	Production Tooling Plan for VP	✓	✓	R	✓
VH-T-40-D3	Upperbody Commercial and Program Agreement (CPA) Package Handoff Complete	✓	✓	✓	
VI-T-20-D8	Stamping Assessment for Feasibility Checkpoint 4 (FC4)	Y	✓	✓	✓
VI-T-20-D9	Stamping Assessment for Feasibility Checkpoint 6 (FC6)	✓	Y	✓	✓
VI-T-30-D3	Upperbody (V1) DPA6 Status	✓	✓	✓	
VI-T-40-D9	Upper Body Manufacturing Requirements and DPA Plan	✓	✓	✓	✓

Figure 4.1.5 – Traffic Light Deliverable Checklist (source: RLE)

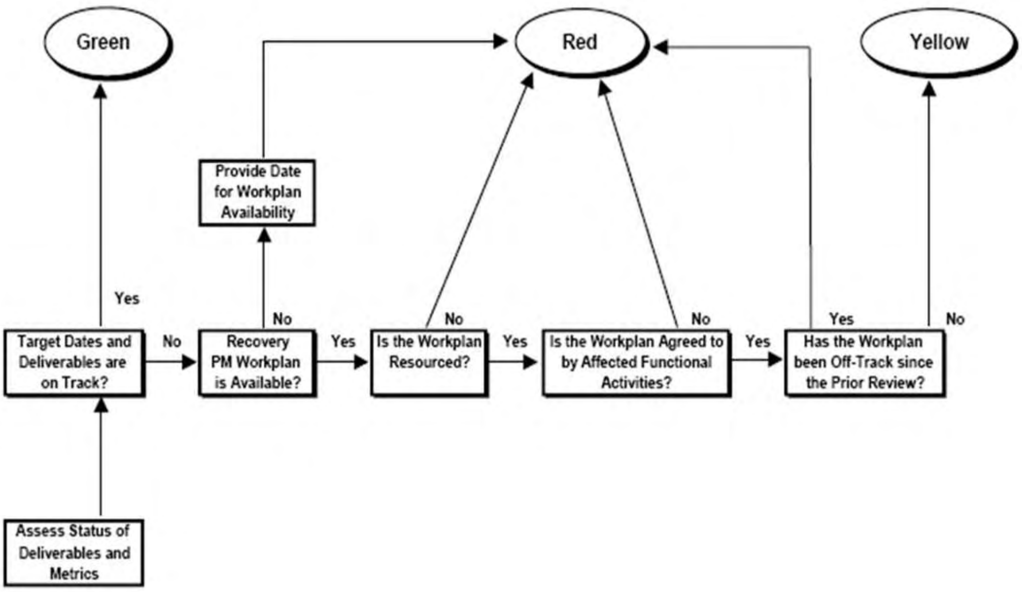


Figure 4.1.6 – Decision Tree for Traffic Light Deliverable Assessment (source: RLE)

The Kanban method, adopted from manufacturing just-in-time techniques and used in Agile software development is a method visualising workflow and limiting Work-In-Progress (WIP), (Anderson, 2010).

Anderson (2010) identified five key aspects to the successful implementation of the Kanban method:

1. Visualise the workflow.

   The workflow of knowledge work is inherently invisible. Visualising the flow of work and making it visible is core to understanding how work proceeds.

2. Limit WIP.

   Limiting Work-in-Progress (WIP) that a pull system is implemented on parts or all of the workflow.

3. Manage Flow.

   The flow of work through each state in the workflow should be monitored, measured and reported. By actively managing the flow the continuous, incremental and evolutionary changes to the system can be evaluated.

4. Make Process Policies Explicit.

   With an explicit understanding of how work is done (e.g. in each department) it is possible to have a rational, empirical and objective discussion of issues.

5. Improve Collaboratively (using models & scientific methods).

   When teams have a shared understanding of theories about work, workflow, process and risk, they are more likelyto be able to build a shared comprehension of a problem and suggest improvement actions.

A common way to vizualise the workflow is a card wall, or Kanban chart (figure 4.1.7), with columns and cards representing the whereabouts of work in the different steps of the workflow.

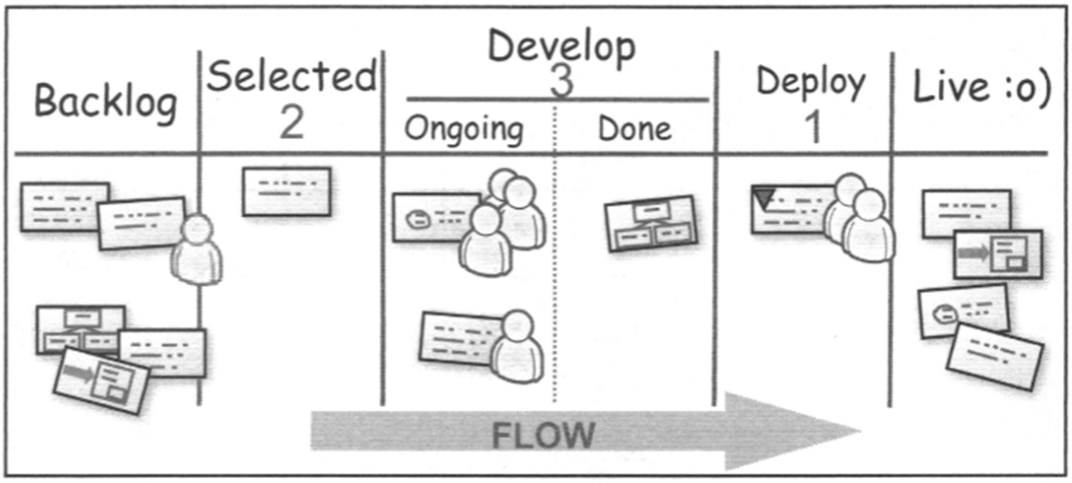


Figure 4.1.7 – Kanban Chart (source: Kniberg, 2011)

With regard to managing flow, Anderson (2010) states that the flow of work through each step of the workflow should be monitored, measured and reported. However, a better method than the card wall is required to represent a complex development process.

Burn-down charts, figure 4.1.8, from software development (Poppendieck & Poppendieck, 2007) show the outstanding work (or backlog) on the vertical axis and time on the horizontal axis.

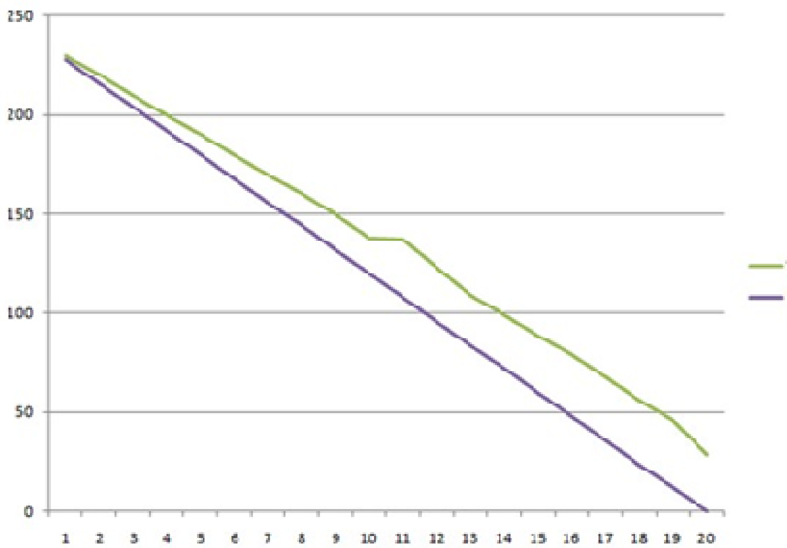


Figure 4.1.8 – Burn-down chart

(source: RLE)

A burn-down chart shows over a period of time how much work remains on a particular activity. A burn-up chart shows the cumulative work being completed over a period of time on a particular activity, figure 4.1.9. The slope of the curve provides an indication of the rate at which work is being done.

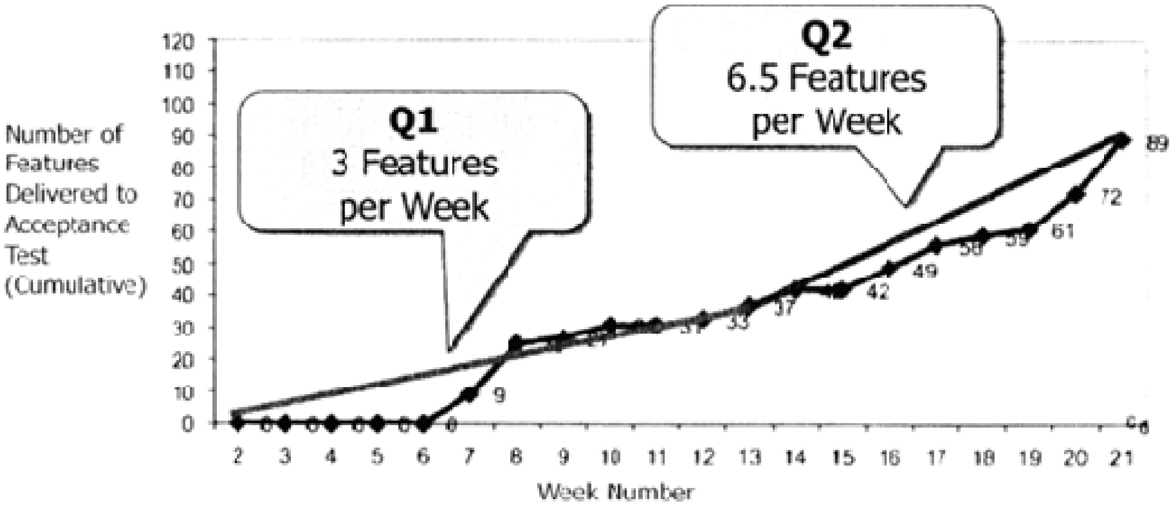


Figure 4.1.9 – Burn-Up Chart (source: Kniberg, 2011)

The Cumulative Flow Diagram (CFD), figure 4.1.10, is a simple adaption of the burn-up chart. Reinertsen (2009) extols its use and describes its applicability for depicting queues over time but states that most organisations do not use CFDs. In figure 4.1.10, a queue is depicted. However, departmental Work-in-Progress (WIP) can also be represented by a CFD, where the right hand boundary of the shaded area would represent the department's burn-up chart of work done.

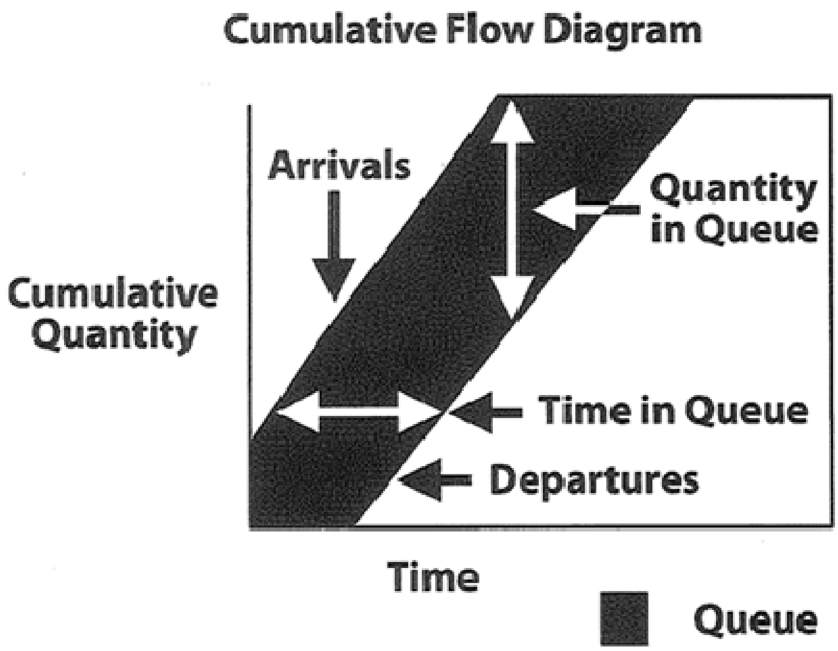


Figure 4.1.10 - Cumulative Flow Diagram (source: Reinertsen, 2009)

Earned value management, figure 4.1.11, with its comparison of earned value against a planned value and the facility to extrapolate estimate at completion provide a useful method.

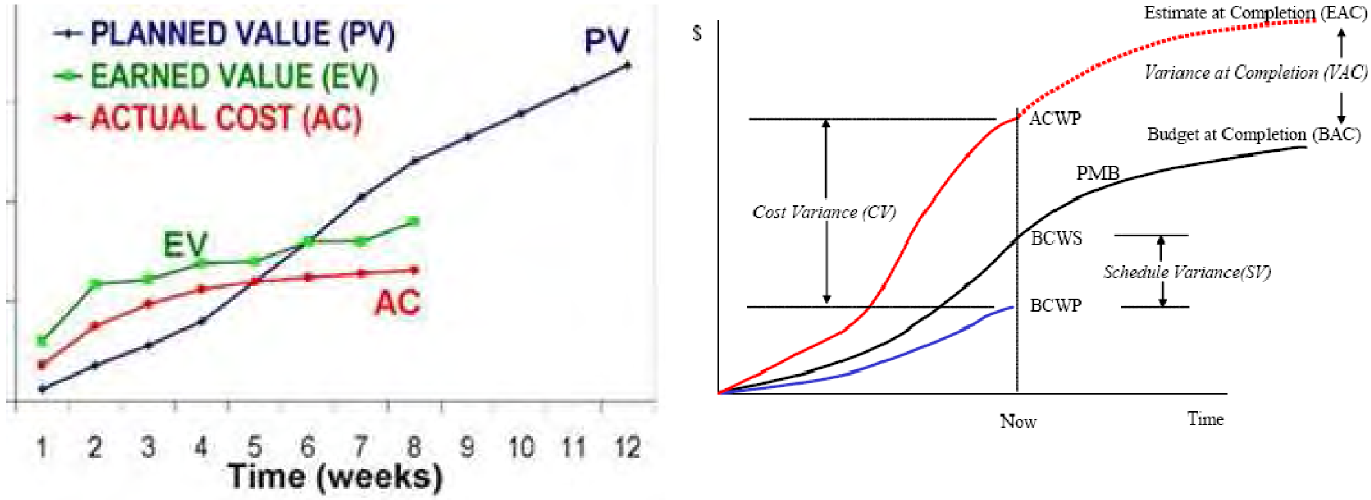


Figure 4.1.11 – Earned Value Management

(source: Lyneis, de Weck, & Eppinger, 2003)

IDEF0 models consider inputs and outputs flowing between activities. O'Donnell and Duffy (2005) used the IDEF0 model to analyse design performance, figure 4.1.12.

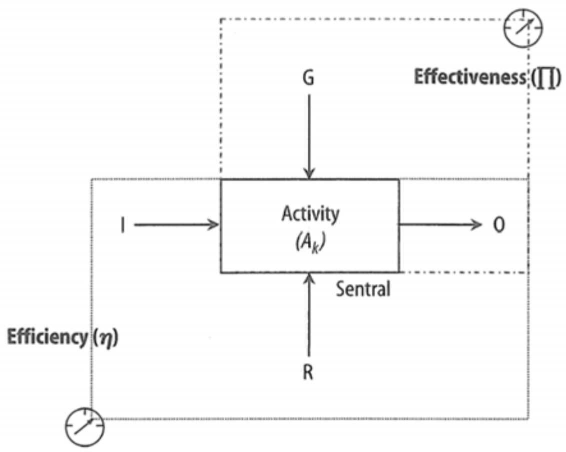


Figure 4.1.12 – IDEF0 Model (O'Donnell & Duffy, 2005)

The IDEF3 model is similar to a basic flowchart but emphasises on flow junctions. It doesn't identify flow but could be part of control mechanism once flow is measured or indicated.

The Design Structure Matrix (DSM), developed by NASA (Collins, et al., 2008), figure 4.1.13, is a two-dimensional grid for mapping relationships between activities and stream-line flow. The DSM is a useful tool but RLE cannot re-schedule the activities in an OEM PD process.

Name		1	2	3	4	5	6	7	8	9	10	11	12
P20: Business Gate 0: Approval to develop concept design	1	1	1										
P100: Customer Specification Review: Reconciled customer requirements, design requirements	2	1	2				2	1	1	2	1		
P103: Establish Organization for Conceptual Design: Assign: Program Manager Project Manager Required PPI/IPD Team Leads / Members	3	1	1	3									
Setup Concept Design File: Concept Design Approval List, Charge Numbers	4			1	4								
P105: Review Lessons Learned Database: Power plant level prelim. design LL checklist	5	1				5							
P110: Generate Power Plant Design Requirements: PPR's, High Level Power Plant Objectives (Preliminary PPR)	6	1	1	1	1		6		1		1		
P120A: Define Process (flow) System: Flow schematic	7			1			1	7	1			1	1
P120B: Define Design Points: Design conditions	8			1			1		8				
P120C: Define Electrical System: Electrical block diagram	9			1			1	1		9		1	1
P120D: Predict Design Condition Performance: Basic system heat & mass balances	10			1				1	1		10	1	
P120E: Identify Major Assemblies: Identification of major assemblies	11			1				1		1	1	11	1
P120F: Define Power Plant Package: Drawing showing component arrangement	12			1			1	1		1	1	1	12

Fig. 4.1.13 - Design Structure Matrix (Collins, et al., 2008)

4.2 Evaluation of Information Flow Measurement Techniques for the Product Development Process

For each of the twelve methods identified, applicability to the automotive PD process was assessed via a Multiple Attribute Decision Analysis (MADA), (Mitten & Gallant, 1997), with particular emphasis on the ability of the technique to be utilised by an ESS such as RLE in conjunction with several different OEM PD processes. The MADA process described by Mitten and Gallant (1997) involves two steps.

The first step was to assign values to the selection criteria identified by the RLE management team. This was achieved by a paired comparison analysis undertaken at RLE, figure 4.2.1. Each criterion was ranked against the others in term of preference, either major (x2) or minor (x1).

Determination of Assigned Value - Paired Comparison

		B	C	D	E	Raw Score	Assigned Value
A	Ease of Use/Application	B2	AC	D2	E2	1	1
B	Reliability		B1	D2	E1	3	3
C	Ease of Output Understanding			D2	E2	1	1
D	Predictive Capability				D1	7	5
E	Real Time Capability					4	4

2 Major Preference
1 Minor Preference

Figure 4.2.1 – Paired Comparison to Determine Assigned Values

If the criterion were judged equivalent then both letters are entered in the chart. The result of these comparisons provided a raw score. For example, 'A' was selected once, whereas 'B' was selected three times (B2+B1). The raw scores were then normalised by the RLE team to produce the assigned values. Step 2 of the process, figure 4.2.2, involved reviewing each of the twelve methods against the analysis criteria.

Evaluation Matrix

No.	Method	Ease of Use/Application	Reliability	Ease of Output Understanding	Predictive Capability	Real Time Capability	Total
	Assigned Value:	1	3	1	5	4	
1	Workflow & BPM	4	9	5	5	12	35
2	Value Stream Mapping	2	12	2	15	8	39
3	GERT	2	12	3	15	8	40
4	Fluid Dynamics	3	4	2	15	12	36
5	Stock & Flow	3	12	3	10	12	40
6	Traffic Light System	5	6	5	5	12	33
7	Kanban Chart	4	12	5	20	16	57
8	Burn-UP/ Burn-down Chart	5	15	5	10	16	51
9	Cumulative Flow Diagram	3	15	4	25	16	63
10	Earned Value Management	4	12	3	25	12	56
11	IDEF0 / IDEF3	1	12	3	15	12	43
12	Design Structure Matrix	3	12	3	10	12	40

Poor	1
Fair	2
Good	3
Very Good	4
Excellent	5

Figure 4.2.2 – Evaluation Matrix for MADA

The methods were judged on a scale of 1 to 5 in terms of a ranking from poor through to excellent. This was then multiplied by the assigned value to give a score, e.g. workflow was judged as excellent in terms of 'Ease of output understanding' and therefore received a score of 5x1=5. The total scores for each method are totalled on the right of figure 4.2.2 and also presented in graphical format in figure 4.2.3.

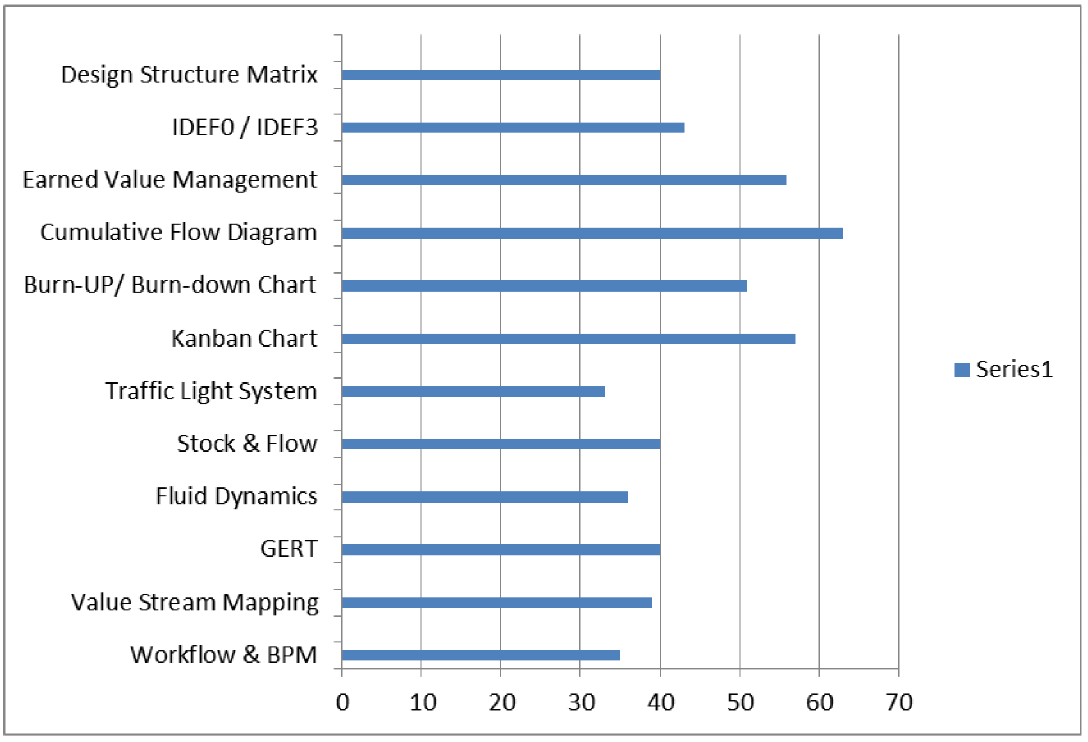


Figure 4.2.3 – Assessment of Information Flow Methods via MADA

The four leading approaches, identified as having potential for application for use by an ESS in monitoring information flows on OEM customer projects, were:

1. The Kanban method with card wall charts.
2. Simple burn-down and burn-up charts.
3. The cumulative flow diagram.
4. Earned value management.

The Kanban is a sutable method but needs to be used in conjunction with the burn-up chart of cumulative flow diagram for reporting purposes. The cumulative flow diagram includes a representation of the burn-up chart and is therefore preferred.

Earned Value Management (EVM) with its comparison of earned value against a planned value, and the facility to extrapolate estimates at completion provides a useful method. This is a strong aspect supporting predictive capability of EVM.

However, figure 4.2.4 (Yeret, 2011) demonstrates the extrapolation possibilities with CFDs. The straight line extrapolation capabilities provide an indication of future performance and also enable the CFD to be used for planning and as a predictive tool.

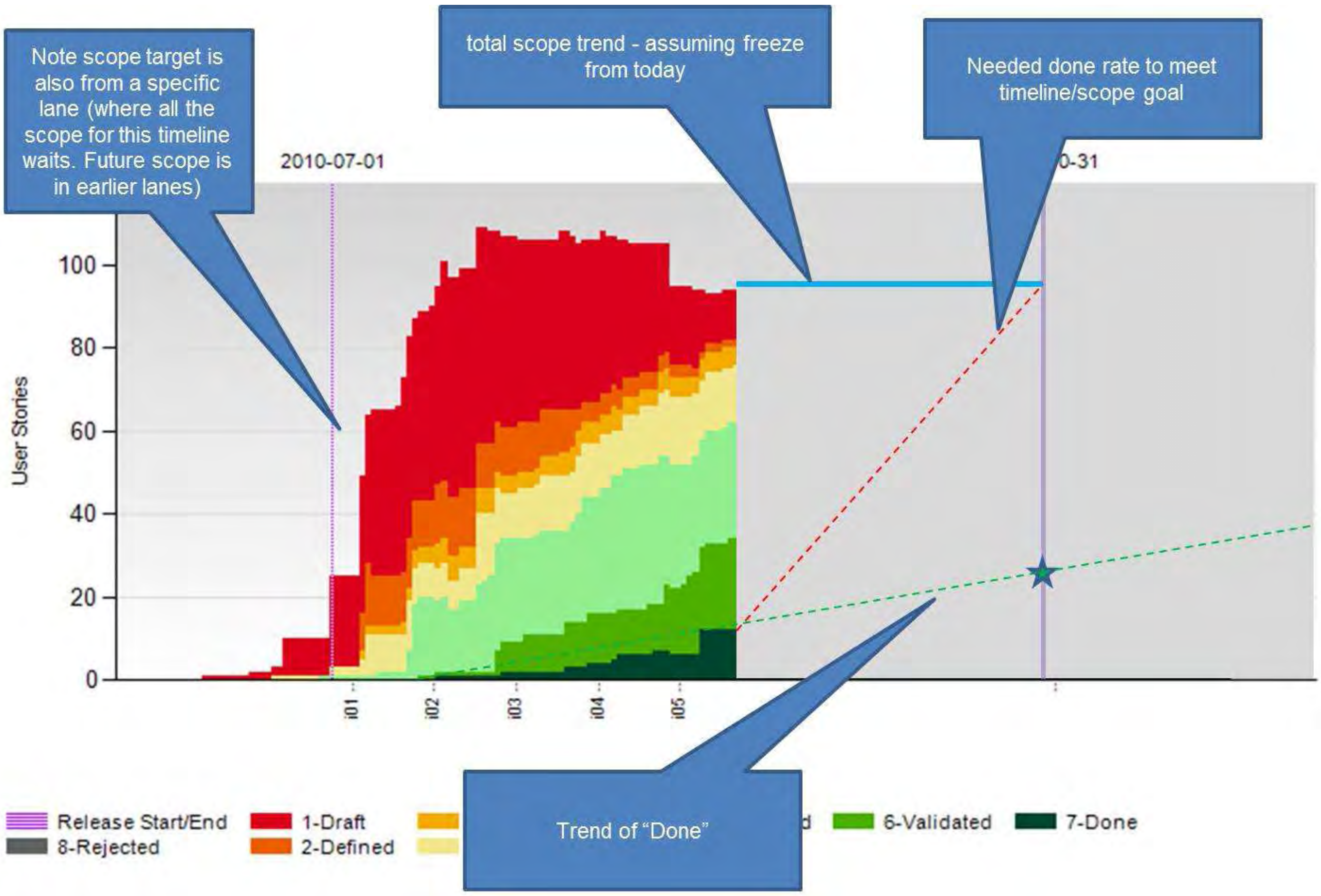


Figure 4.2.4 – Extrapolation with CFD (source: Yeret, 2011)

4.3 Conclusions

After considering all aspects, the Cumulative Flow Diagram (CFD) was chosen for further exploration and development. The advantage of the CFD is that it delivers a visualisation the rate of flow of work being done and also provides a depiction of the work sitting in each stage of the process, i.e. the Work-In-Progress (WIP).

5 Evaluation of Cumulative Flow Diagrams in Development Processes

One of the key features of the Cumulative Flow Diagram (CFD) is that it delivers a visualisation of the rate of flow of work being done and also provides a depiction of the work sitting in each stage of the process, i.e. the Work-In-Progress (WIP).

5.1 Current Application of CFDs in Development Processes

The CFD has recently been employed in the software development industry. Hewlett Packard has recommended their broader adoption and use colour in their chart (Iberle, 2010). Figure 5.1.1 demonstrates the use of a CFD to show work in a backlog (i.e. not yet started), WIP, executed work needing a fix or rework and finally fully completed.

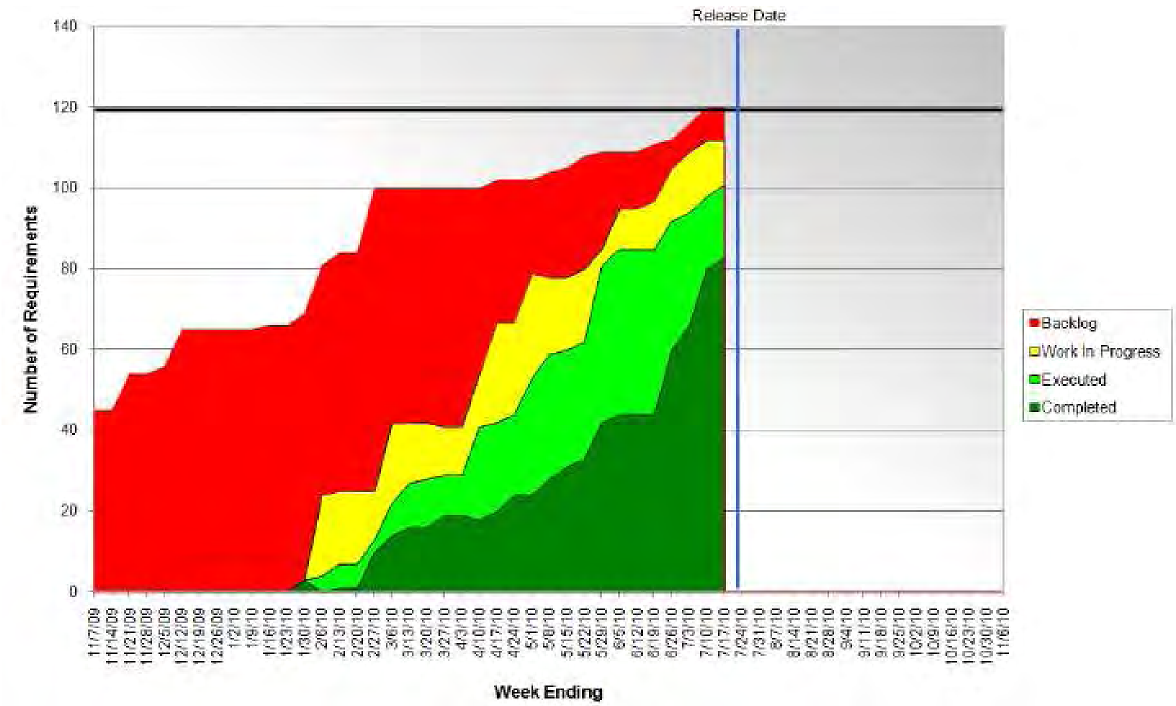


Figure 5.1.1 - Cumulative Flow Diagram use at Hewlett Packard

(source: Iberle, 2010)

Whilst at first glance this resembles the status charts used to depict traffic light system metrics, the CFD can provide a lot more information about a process. Petersen & Wohlin, (2010) studied the use of CFDs in an industrial context at Ericsson and concluded that the visualisation and measures are especially valuable for developing large scale products involving many teams and tasks as here high levels of process transparency are important. Figure 5.1.2 shows the chart used at Ericsson (Petersen & Wohlin, 2010) which also designates the hand-overs between activities in the overall process.

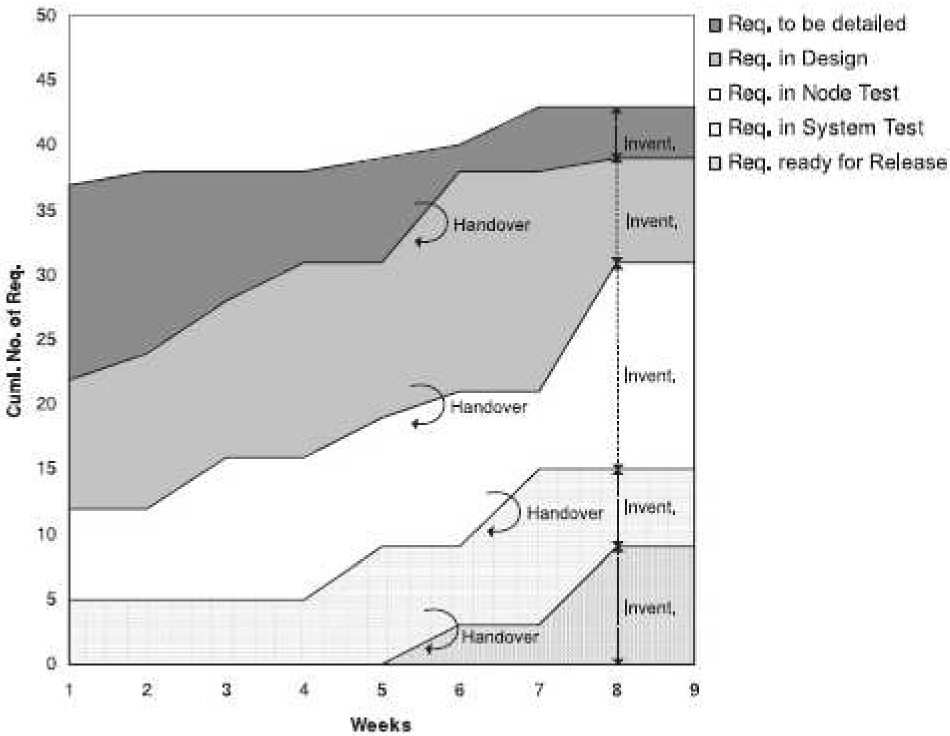


Figure 5.1.2 - Ericsson Software Engineering

(source: Petersen and Wohlin, 2010)

Academic search tools using the university online library and associated journals yielded zero results for "cumulative flow diagram" with "automotive product development". Further research investigation, using the author's extensive industry network, has shown no evidence of this method being used in the professional context of the automotive industry.

However, the automotive PD process is more complex than the examples shown and the CFD needs to be modified to cover more activities than considered by Iberle (2010) and Petersen and Wohlin (2010).

5.2 Verification of Applicability of the CFD to the Automotive PD Process

The CFD technique had potential to meet the identified need of information flow tracking but further verification of its applicability to the automotive PD process is required. Specifically, can the CFD be made functional in the automotive environment and is the correct data available to enable its construction?

Examination of OEM project control records revealed the use of 'glide path' charts (figure 5.2.1) that are examples of burn-up charts. These charts track release of data from different departments in the PD process and would suggest the basic data required to build a CFD chart for the automotive PD process already exists.

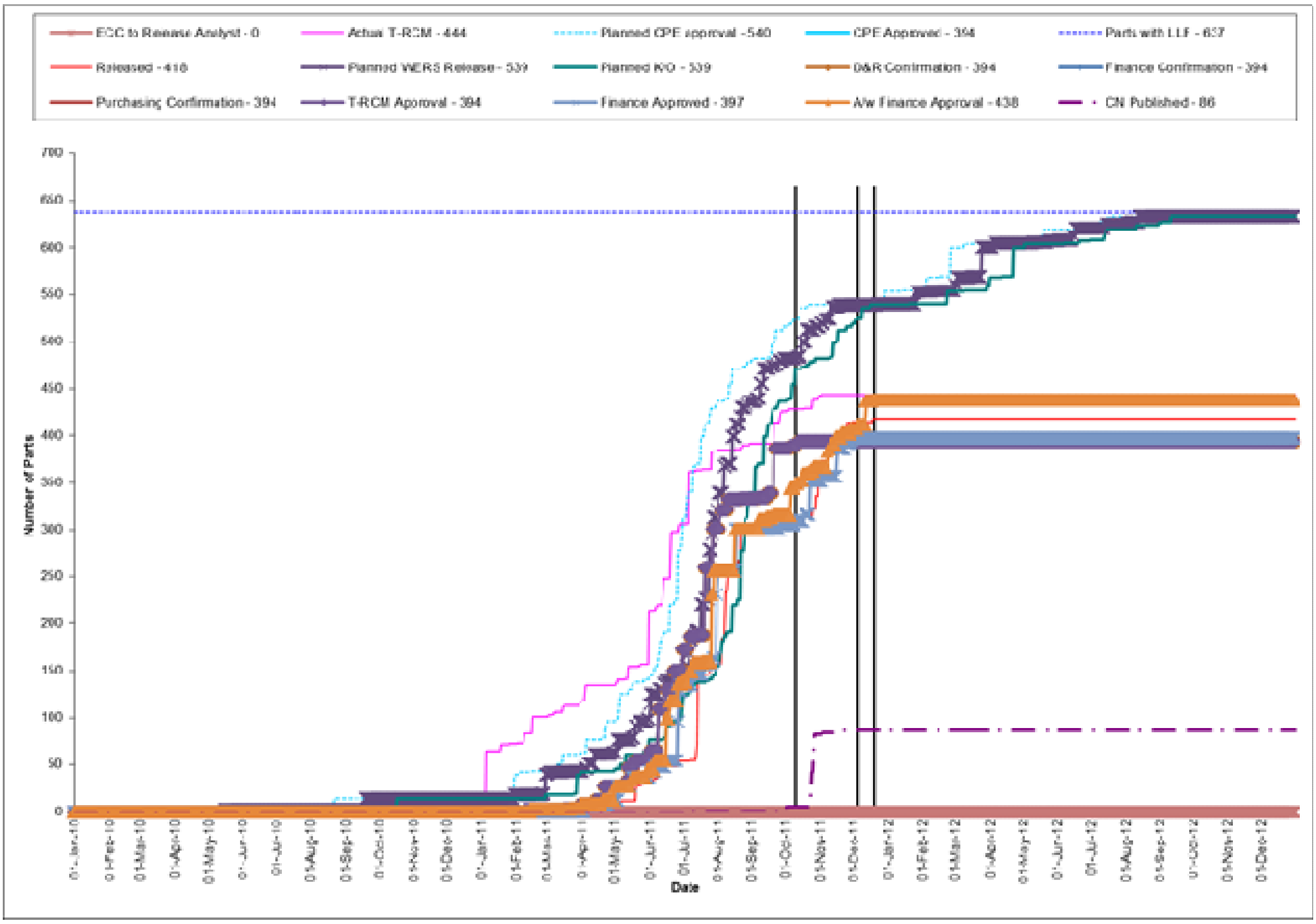


Figure 5.2.1 – Glide Path Data from Automotive OEM PD Process (source: RLE)

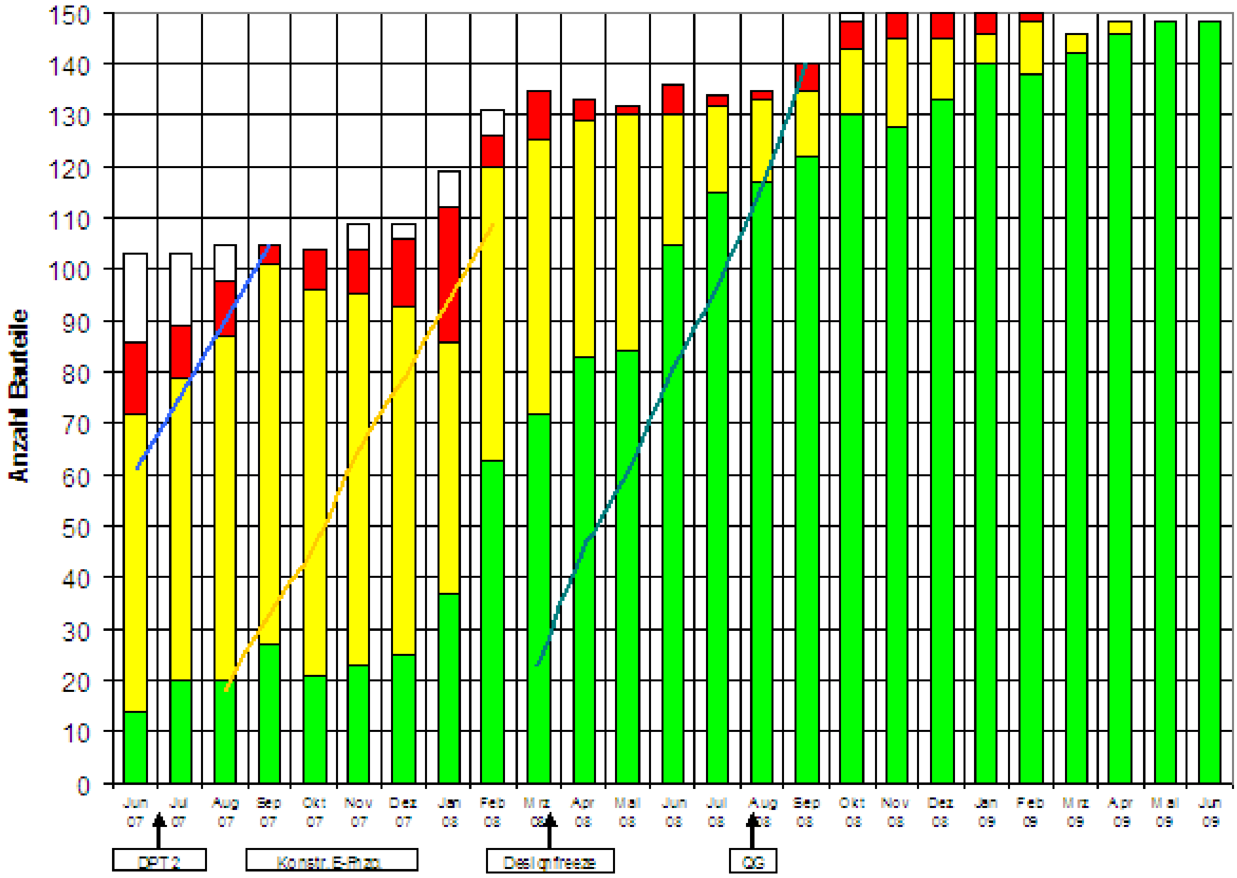


Figure 5.2.2 – Traffic Light System Metrics for Manufacturing Feasibility (source: RLE)

Additionally, investigation into RLE project records revealed the use of traffic light system metric charts on a Mercedes project at RLE's Stuttgart office, figure 5.2.2. Whilst at first glance this resembles a CFD, it is in fact a simple indication on a monthly basis of the number of parts signed off as feasible (green), conditionally feasible (yellow), not feasible (red) and yet to be considered (white). This data could also be used as the basis of a CFD chart. The angled blue line represents the target number parts that should be in feasibility assessment by a certain month. The angled yellow line provides target for the number of parts to be deemed feasible by a given month. The dark green line represents the dates when the parts should be fully toleranced and the material specifications agreed. These target lines provide an interesting concept that could form the basis of a planning function on a CFD chart.

5.2.1 Potential of the CFD at the RLE CAD Department

In order to verify the use of the CFD in the automotive PD process, information flow on a project in progress at RLE UK's CAD department was reviewed. Investigation of the CAD department's control records showed only output from the CAD process was being tracked, figure 5.2.1.1.

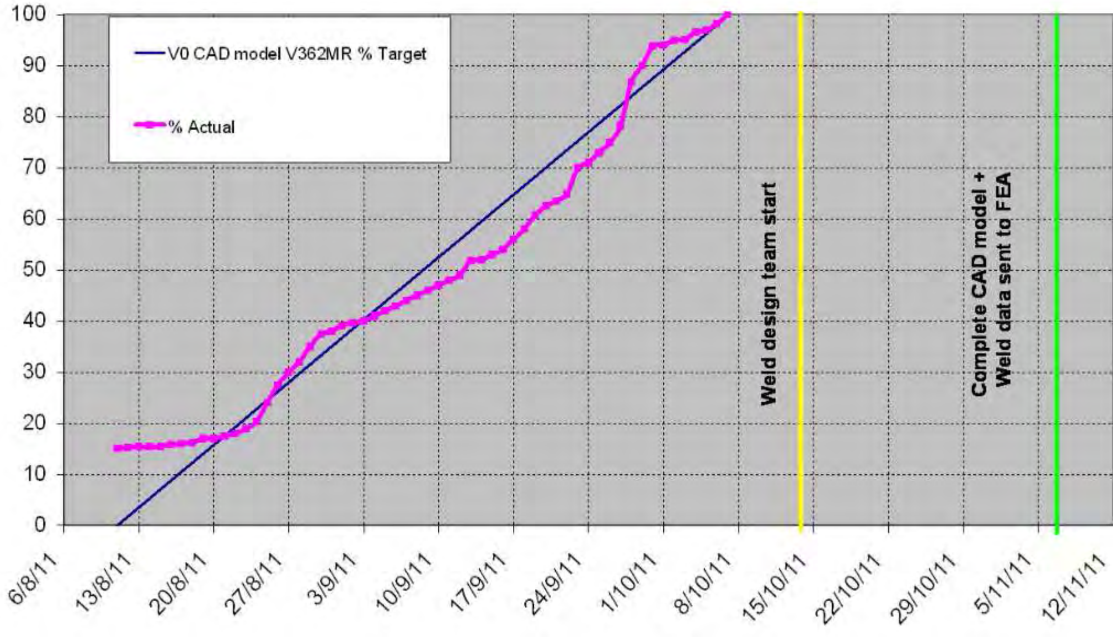


Figure 5.2.1.1 – RLE V0 CAD Release Data

The '% Actual' line on the graph shows output from RLE UK CAD department and is similar to the burn-up chart described earlier in this report at section 6.4. Whilst this demonstrates the 100% of the CAD data will be released to the weld design team and FEA (CAE) teams prior to the target dates, it is a lagging indicator of performance, i.e. it only shows when the work was complete. If the date of the work's arrival at the CAD department had also been plotted on the same graph, Work-in-Progress (WIP) could have been monitored, figures 5.2.1.2 and 5.2.1.3. This shaded area between the work arriving (red dotted line) and its completion (green dotted line) in figure 5.2.1.3 is typically referred to as a funnel of work on a CFD chart (Gonzales-Rivas & Larsson, 2011).

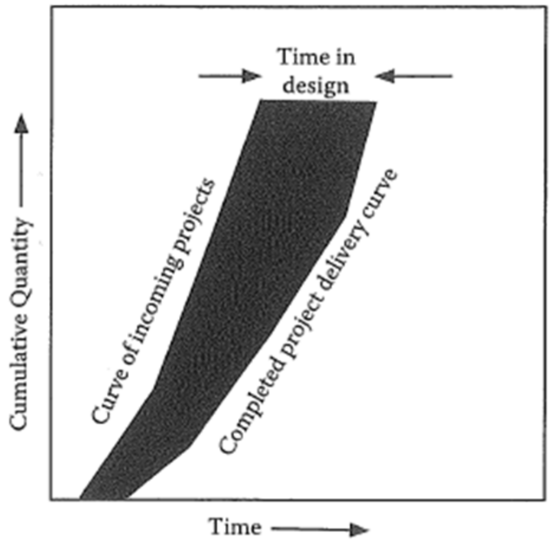


Figure 5.2.1.2 – Work in Progress Funnel depiction via Cumulative Flow Diagram (source: Gonzales-Rivas & Larsson, 2011)

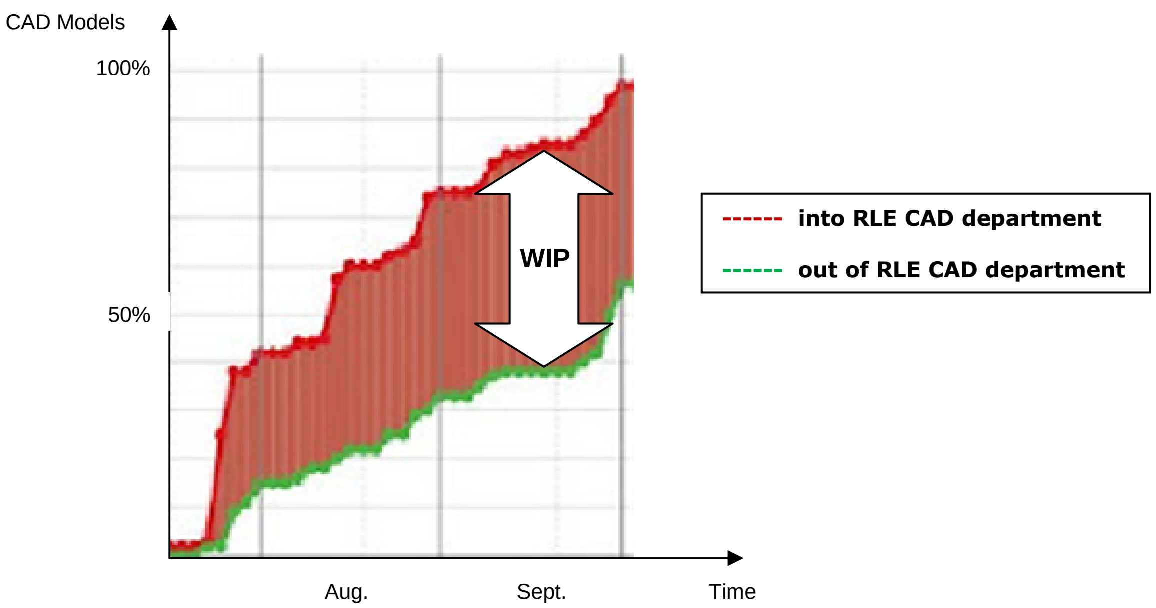


Fig 5.2.1.3 – Example showing how CAD Work-in-Progress could have been portrayed via a CFD (source: RLE)

The identification of the WIP provides a measure of the amount of work in the department on any given day. This enables resource levels, i.e. the number of CAD operators required, to be calculated. Extrapolation of the boundaries of the WIP funnel on the chart provides an indication of future WIP, and thus future resource requirement.

This demonstration at RLE is analogous to the Hewlett Packard case (Iberle, 2010), in that it only considers one department. If the status of the backlog of the parts not having reached the CAD department could be understood then a superior project control plan could be developed. In the Ericsson case (Petersen & Wohlin, 2010) the handovers between departments in the development process are considered. This is what is required in the automotive PD process. However, the complexity of the automotive PD process needs to be considered to determine the precise area of application.

Figure 5.2.1.4 (Klipp, 2010) provides a very useful overview on the CFD and the information it can portray.

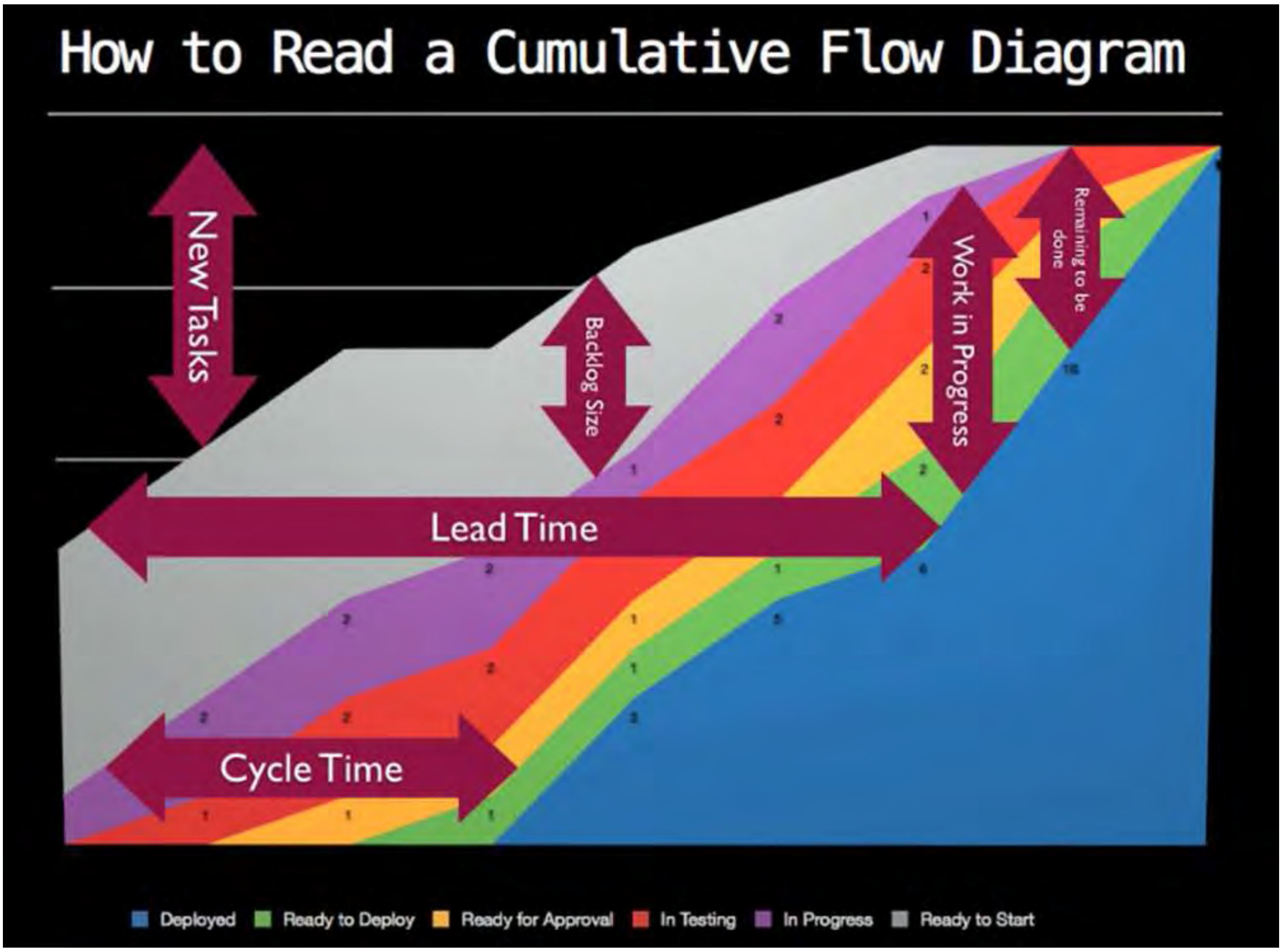


Figure 5.2.1.4 – How to Read a Cumulative Flow Diagram (source: Klipp, 2011)

On reflecting on this chart, the author recognised that the CFD chart could be extended to include a series of activities in the automotive PD process, e.g. the areas of the chart and handovers could be used to represent work:

1. Still in the Design Studio.
2. Released to Product Engineering but not started.
3. In progress in the Product Engineering CAD department.
4. Released to Manufacturing Engineering for feasibility.
5. In progress in at Weld Design.
6. Released to the CAE department for Finite Element Analysis.

This is the basis of the Extended Cumulative Flow Diagram (ECFD). The extrapolation capabilities of the CFD could then be used to better control the whole PD process.

5.3 Complexity in Product Development

The PD task network can consist of thousands of interactions. In figure 5.3.1, 1245 directed information flows between 466 development tasks in a single development project were mapped (Braha & Bar-Yam, 2004).

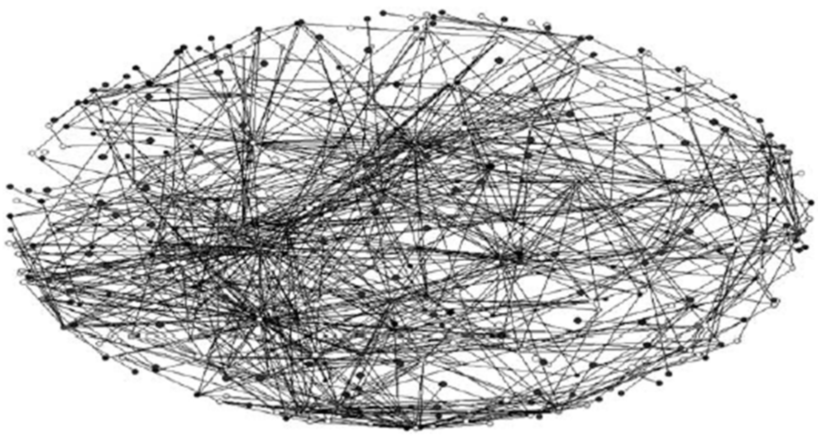


Figure 5.3.1 - Information Flow Structure in a Large Scale PD Process

(source: Braha & Bar-Yam, 2004)

Given this level of complexity, the specific area of application of the CFD within the automotive PD process needs to be considered. Figure 5.3.2 shows an example of the complexity of interactions in a typical development process. However, the interaction between different phases of the development, i.e. across major gateways (BG1 & BG3), is less complex.

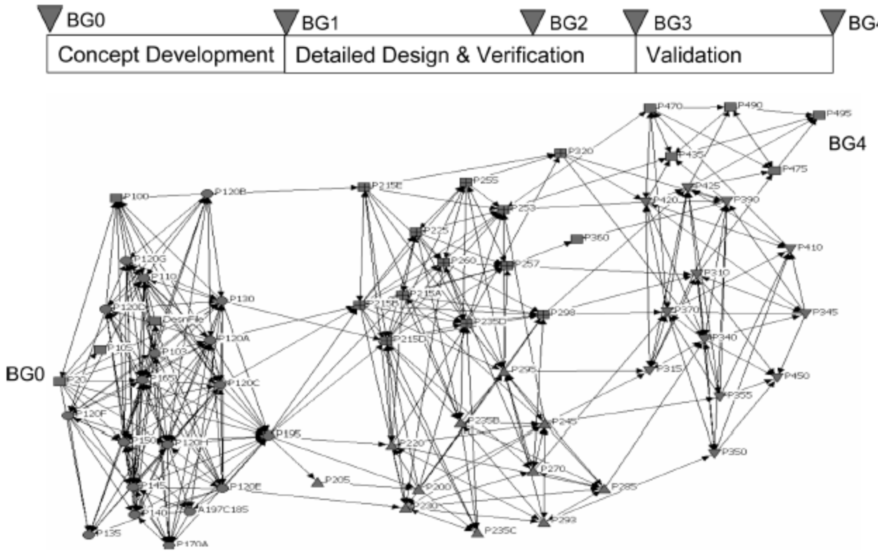


Figure 5.3.2 – Network Map (PERT) of a Product Development Process (source: Collins, et al., 2008)

These links or interactions would not be immediately obvious from the stage-gate flow chart, nor would they be clear from a Gantt chart. In a typical automotive OEM, three major departments contribute to the core development tasks of the PD process (figure 5.3.3). It is at the interactions between these departments that bottlenecks typically occur and the CFD can initially be most effectively utilised.

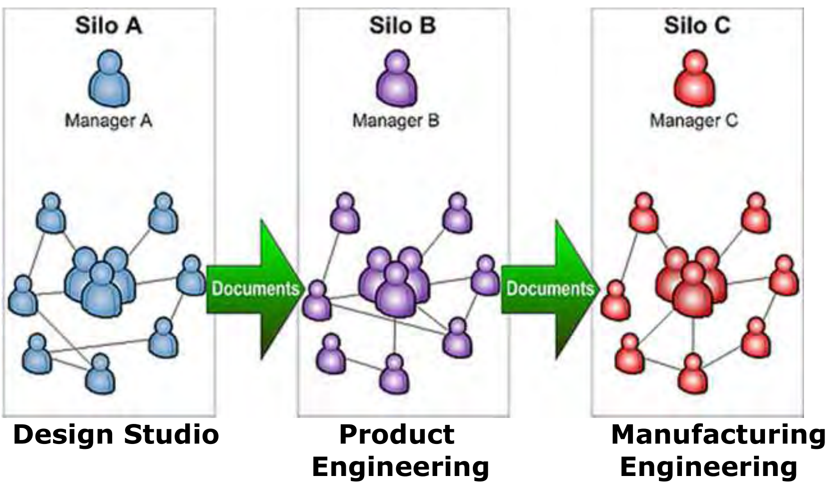


Figure 5.3.3 – Automotive OEM PD Communication (source: RLE)

5.3.1 The Automotive PD Process

In an approach similar to the V-process discussed in research project 2, some OEMs have recognised this complexity of the overall PD process and broken the task in to different levels (figure 5.3.1.1). The overall vehicle project plan is specified as level 1, the integration or interaction plan as level 2 and module development teams as level 3. Sub-system development is level 4 and individual work plans for individual parts or components level 5.

As referred to previously and commented on by Wheelwright & Clark (1992), Browning & Ramasesh (2007) and Bicheno (2008), it is the interactions between activities, i.e. the level 2 integration plan, that demand greater focus. Here, the key interactions between the various Program Module Teams (PMT), e.g. Body Upper Structure, and Program Attribute Teams (PAT), e.g. Craftsmanship, should be described. In the author's experience, in several OEM PD systems, this level 2 integration plan is often ill-considered. As demonstrated by the case study Gantt chart in chapter 3 (Figure 3.1.1) the links between departmental work-streams are often omitted.

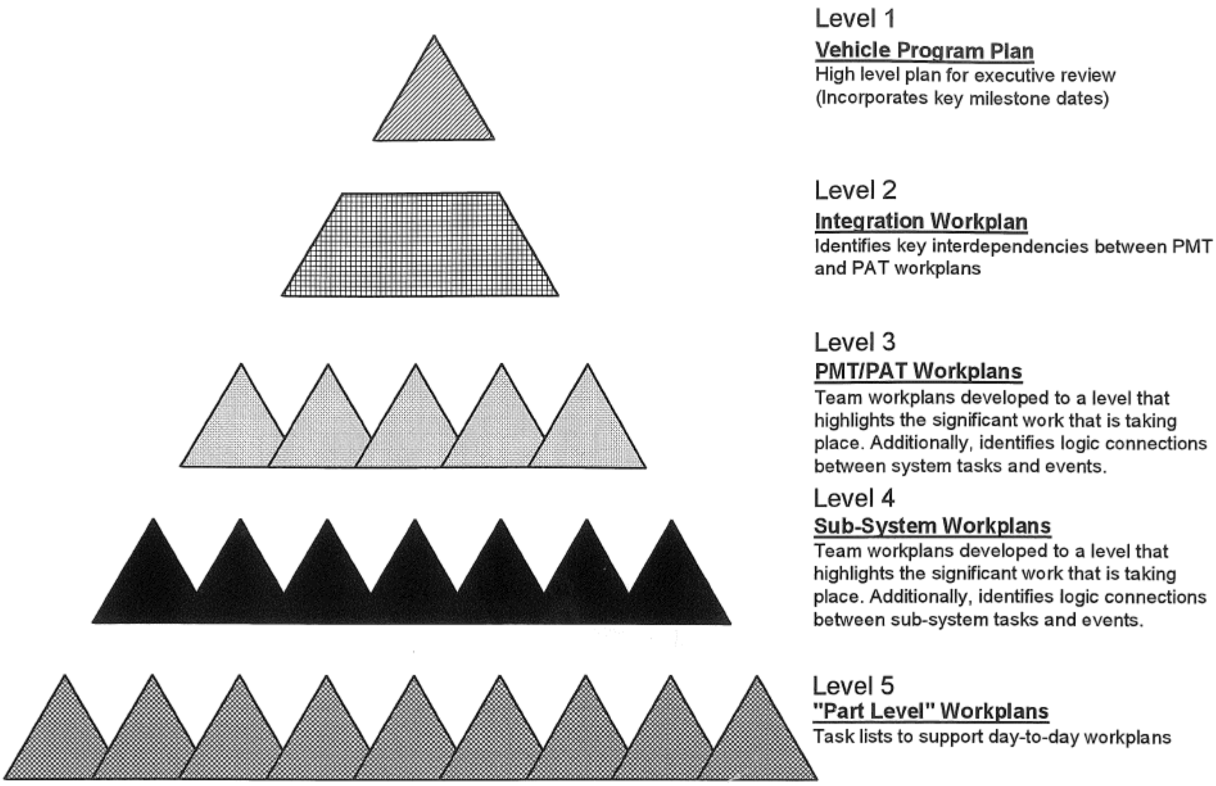


Figure 5.3.1.1 – PD Process Levels (source: RLE)

However, as shown by the linking arrows in figure 5.3.1.2, some of the interactions are at least considered by some OEMs' Gantt charts. Here, the interactions between the design studio work-stream including CAD feasibility checks (FC0 – FC5) at 'A', engineering CAE Upper Body Virtual Prototypes (UPV0 – UPV2) at 'B' and manufacturing CAM virtual builds at 'C' are represented. The information flow at the interactions represented by the linking arrows is where we need to focus our attention.

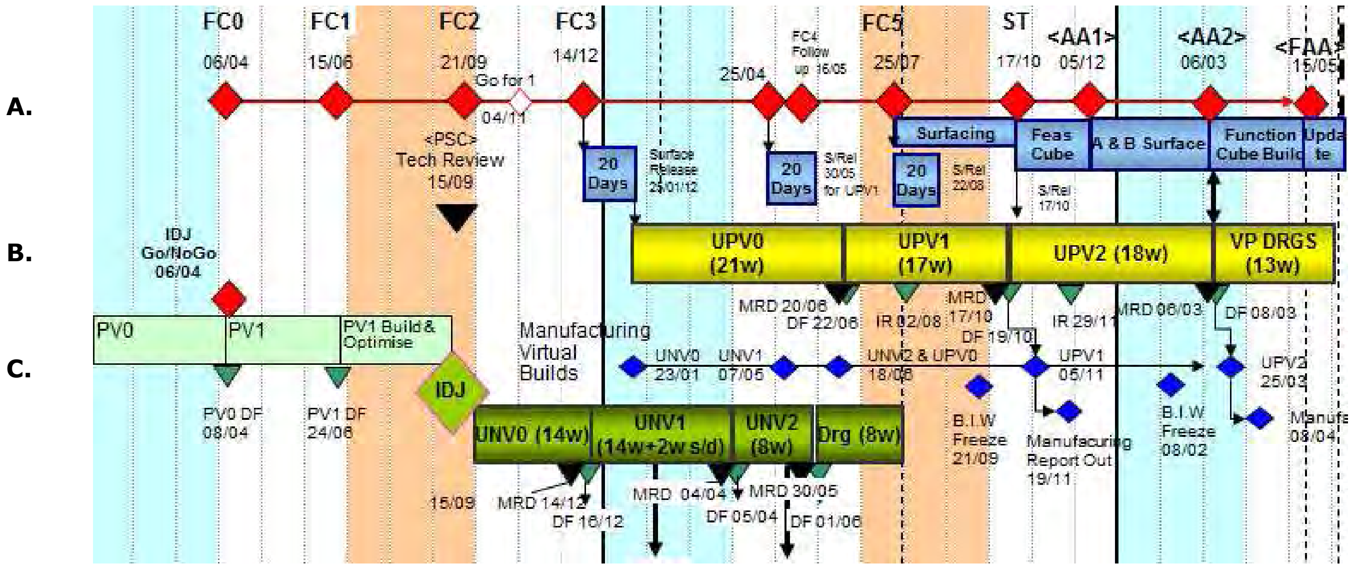


Figure 5.3.1.2 - Interaction between Automotive PD Work-streams (source: RLE)

The author has seen many instances where new teams of relatively inexperienced designers and engineers have been put into development projects without these interactions being clearly explained. This leads to a totally uncoordinated project and budgets and timing targets being missed.

5.4 Conclusions

The Cumulative Flow Diagram (CFD) is used in development processes in other industries and the basic data needed to apply it in the automotive industry PD process already exists. The CFD should be further developed to monitor information flows between departments in the automotive PD process.

6 Creation and Development of the Extended Cumulative Flow Diagram at RLE

The development of the Extended Cumulative Flow Diagram (ECFD), to better represent the interactions between several departments in the automotive PD process was conducted at RLE UK. An Extended Cumulative Flow Diagram (ECFD) was proposed that considered the workload and output of information from upstream departments in the automotive PD process, and could be used as a predictive tool for downstream planning and project control purposes.

The benefits offered by the Kanban approach (Figure 6.1) were presented by the author to the management of RLE UK in December 2011:

1. Visualise the Workflow
2. Limit WIP
3. Manage Flow

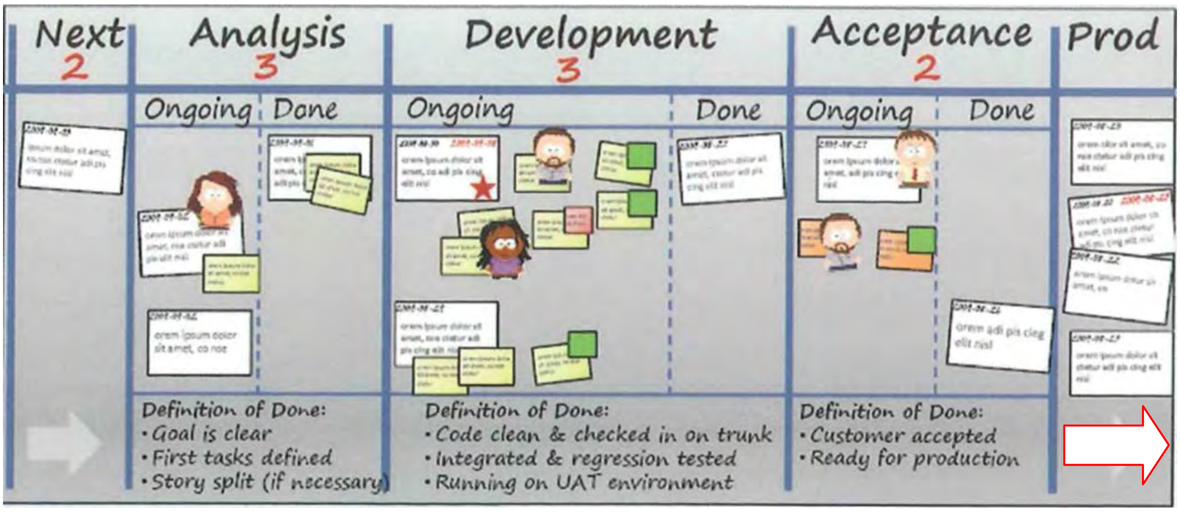


Figure 6.1 – Kanban as initially discussed with RLE UK Management (source: Kniberg, 2011)

6.1 The Concept of the Extended Cumulative Flow Diagram

Next, the possibilities offered by the use of CFDs to visualise and control information flow was discussed. Figure 6.1.1 is offered as a working document from the meeting.

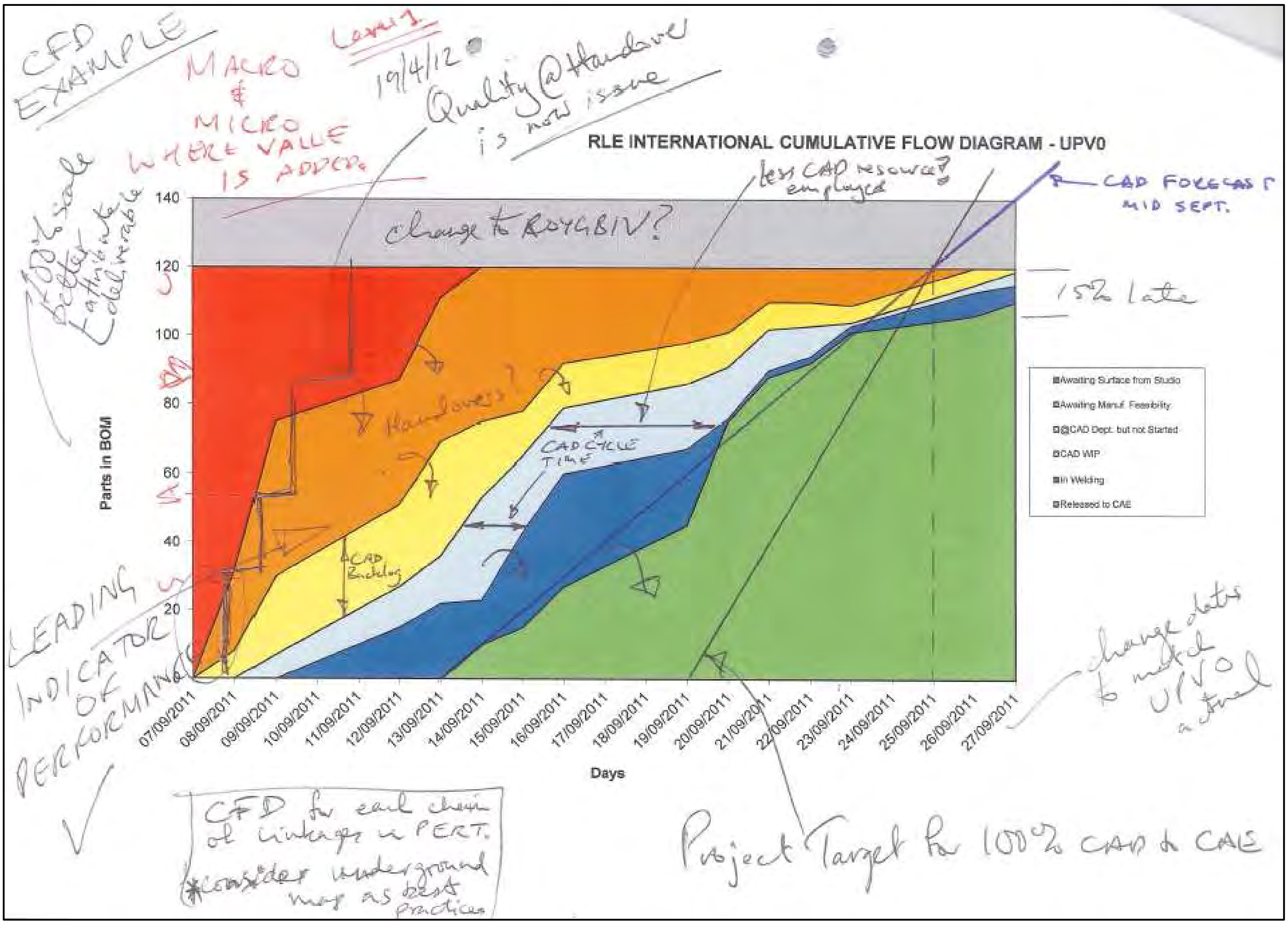


Figure 6.1.1 – CFD as initially discussed with RLE UK Management

The RLE management team agreed the approach was new and unique and presented an innovative perspective on information flow in the automotive PD process.

The 'x' axis represents time and the 'y' axis the work to be done. In the RLE UK case this was set as the number of parts in a Bill of Materials (BOM) to be processed by the CAD department. However, the 'y' axis can be any measure of work to be done that relies on progress through a series of departments.

The use of the ECFD as a tool for planning staged handovers between departments was explored, figure 6.1.2, and it was proposed that an ideal plan for managing information for steady flow would have parallel lines bounding the 'funnels'. These are analogous to the target lines shown in the Mercedes project chart at figure 5.2.2. This would provide a plan for constant WIP over a period of time in each of the departments. This would facilitate better resources planning. Additionally, as the main focus in this case was the CAD department, a buffer should be included to ensure the CAD team is kept fully utilised.

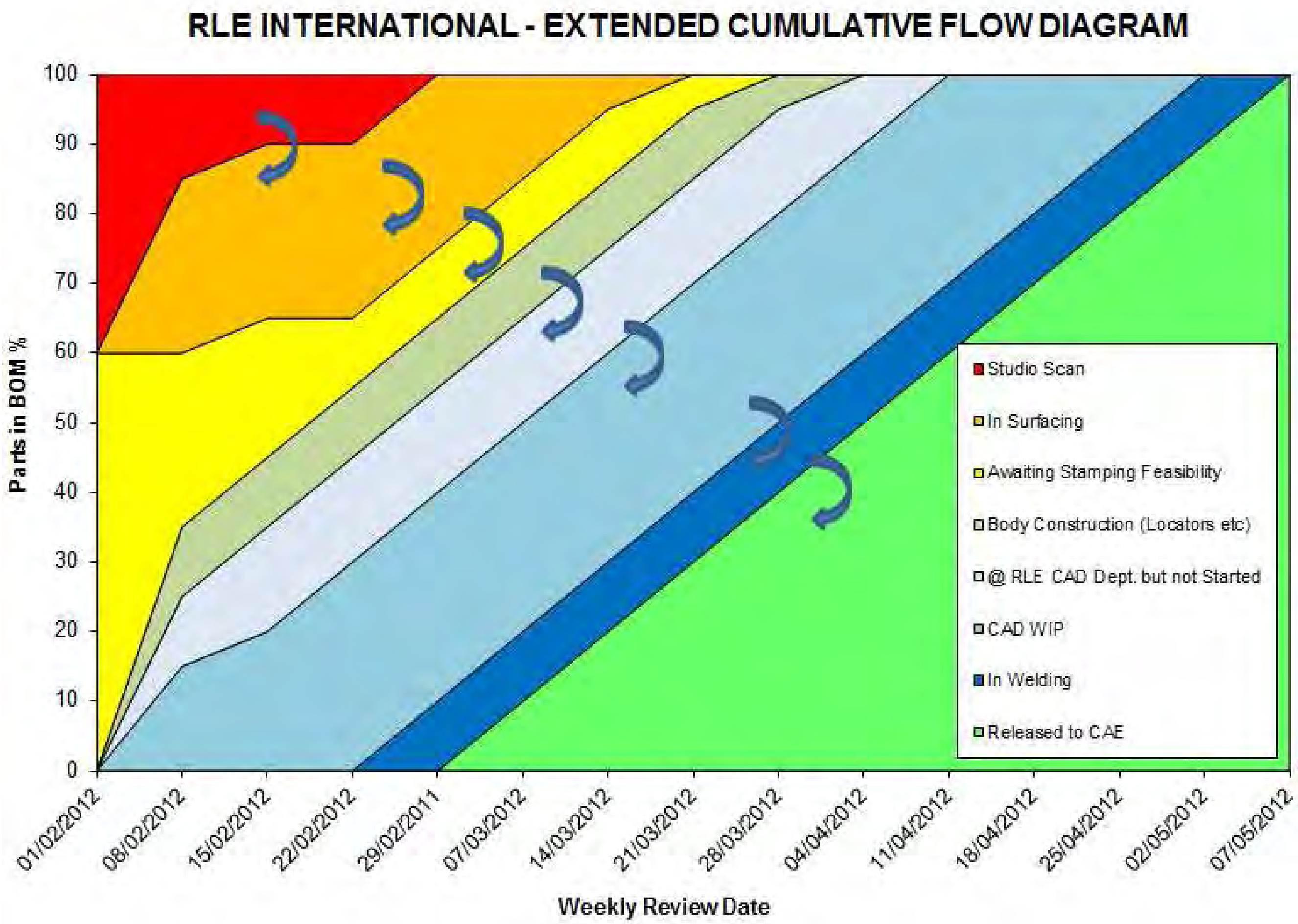


Figure 6.1.2 – ECFD as a Planning Tool

It was agreed by the RLE team to use an Extended Cumulative Flow Diagram (ECFD) to plan and monitor the project going forward. The application of new ECFD tool would provide a tool that:

1 Considers information flow in the planning stage.

2 Considers the sequential handovers between departments.

3 Provides a multi-department WIP planning tool.

4 Considers performance in prior stages to predict WIP movements during projects.

5 Facilitates extrapolation towards gateway timing.

6 Identifies where bottlenecks are occurring.

7 Enables real-time decision making on required resource levels.

In summary, this approach provides a unique approach to the automotive PD process by taking the original CFD tool, adding multi-department planning and control capability to provide measuring and visualisation of in-process information flow.

6.2 Construction of the CFD

Both Microsoft Project and Excel were trialled to depict the ECFD with Excel being chosen for the final implementation. Yeret (2011), figure 6.2.1, provides a useful introduction to the construction of a CFD from a Kanban type analysis of where work is in the development process.

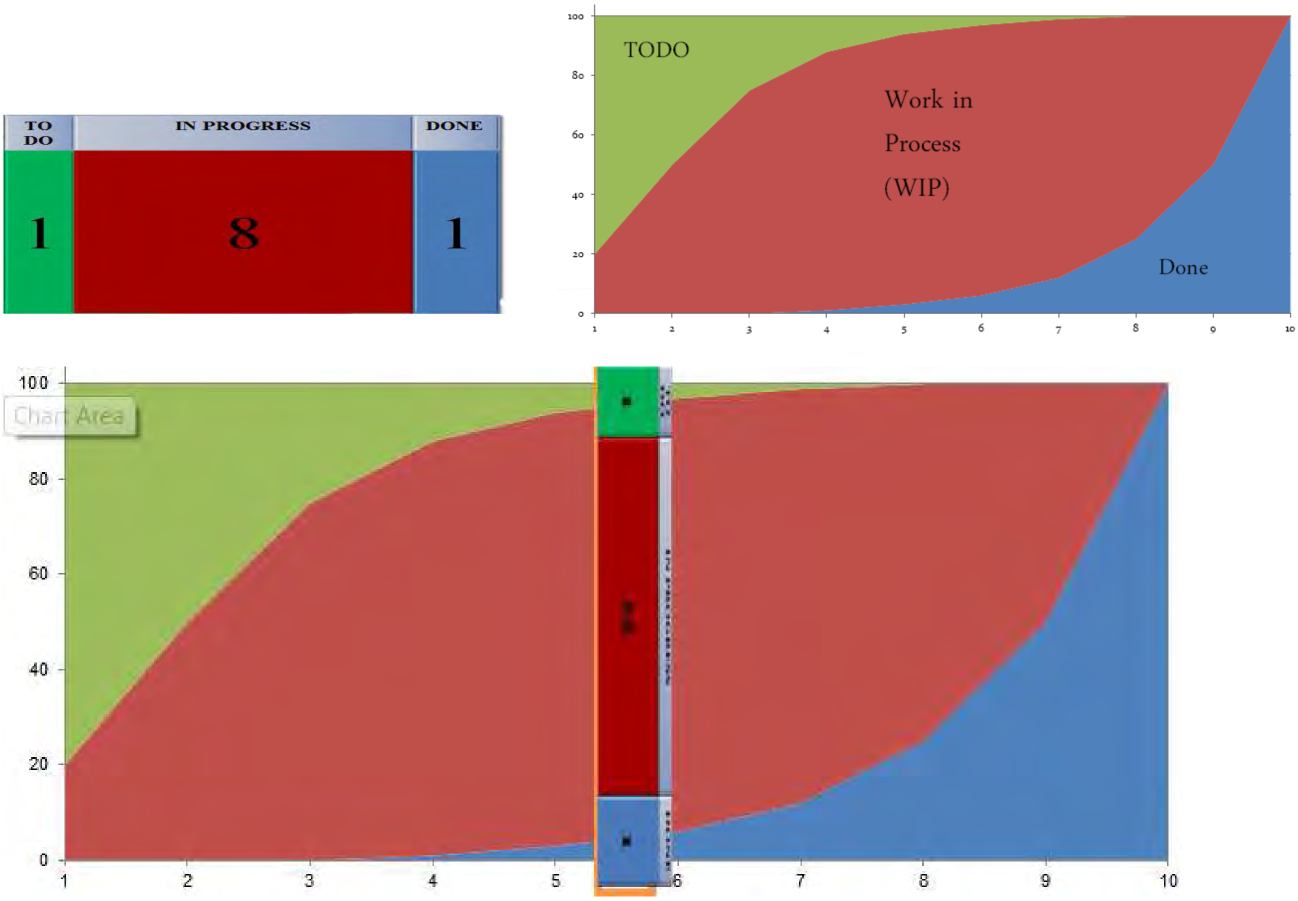


Figure 6.2.1 – Construction of a CFD chart from Excel Kanban Data

This construction techniques was used to construct the RLE ECFD in excel.

6.3 Evaluation and Validation of ECFD Chart for Information Flow Assessment

Oppenheim (2010) describes that PD flow modelling could be tested by mapping of shorter, low-risk, legacy-based projects or project segments using maximum concurrency of tasks within the enterprise. Here the use of the ECFD is applied via an empirical test to a project that involves relatively minor exterior changes to an existing vehicle design. The project chosen for this evaluation was the re-timed project discussed in the case study in chapter 3 of this report. The project was chosen because of the concurrency of tasks at RLE and at the customer's design studio, CAE and manufacturing engineering department. The project was already underway to the revised timing plan, and Gantt charts were being used to track the project, figure 6.3.1. These excel charts were being used to report issues but offered no predictive capability or solutions.

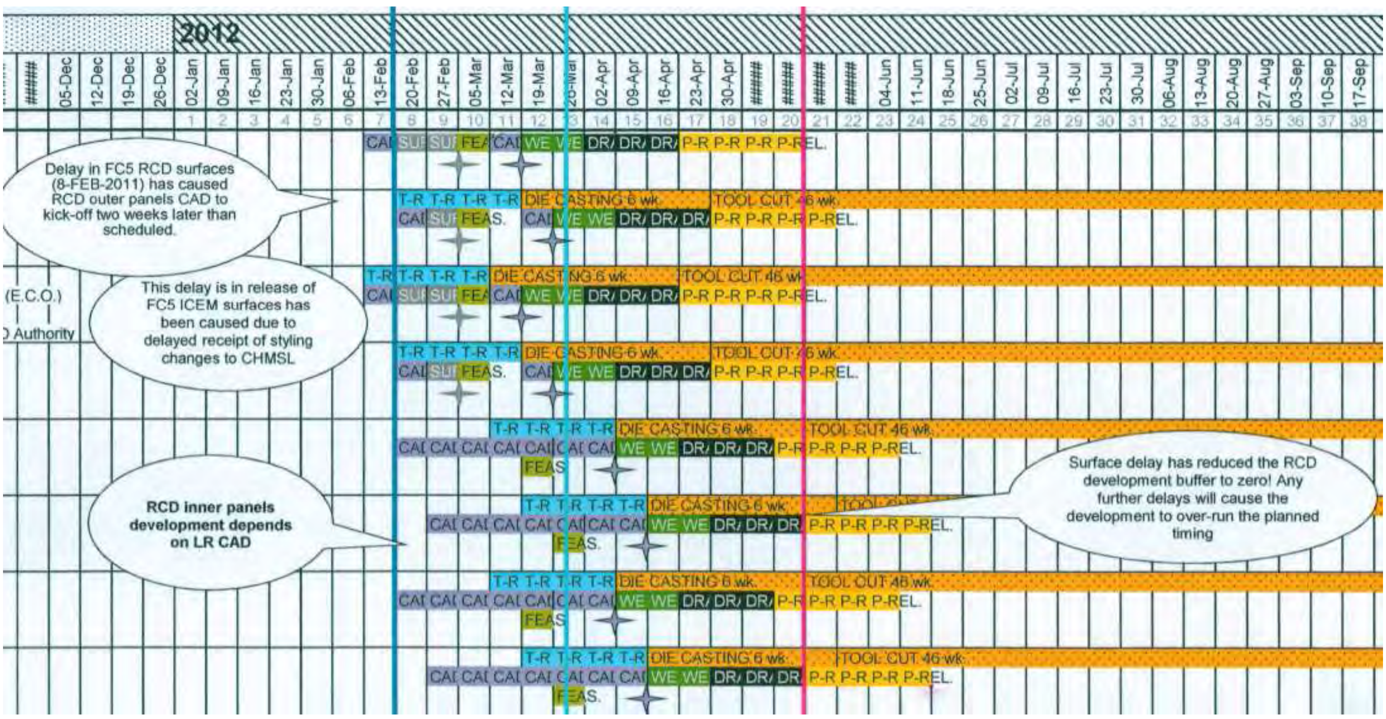


Figure 6.3.1 – Gantt Chart for Timing and Issue Reporting

6.3.1 Application of the Extended Cumulative Flow Diagram

Firstly, the necessary flow of information to meet the new FDJ timing was presented and agreed by the RLE team via a Kanban chart , figure 6.3.1.1.

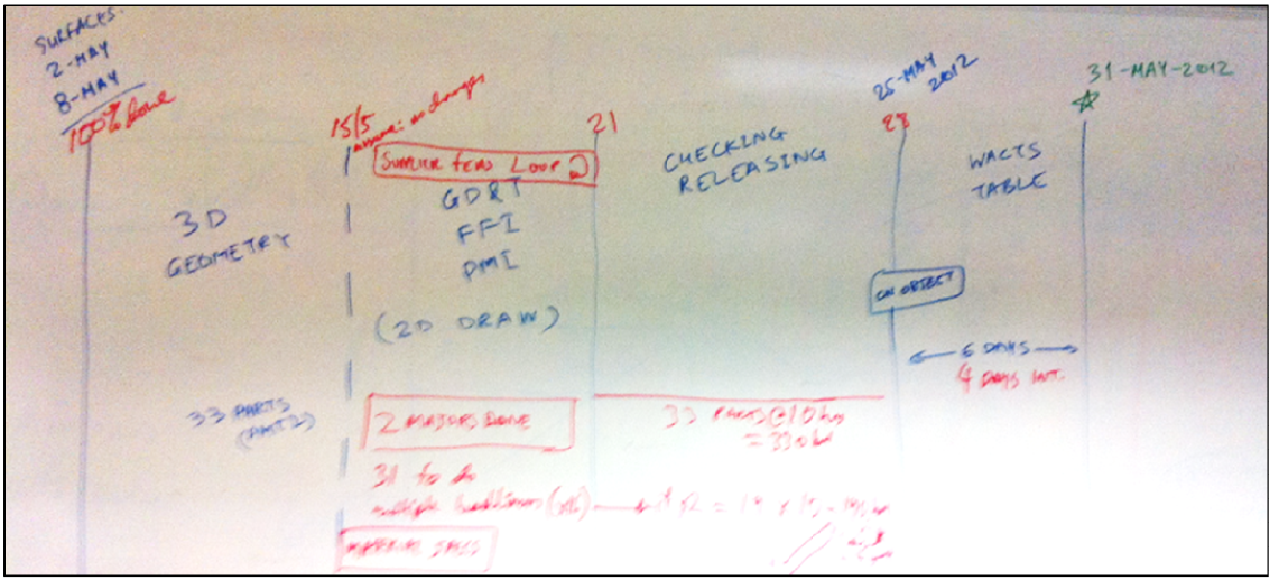


Figure 6.3.1.1 – Kanban chart as discussed at RLE

This plan was then converted to Excel, figure 6.3.1.2. Again, the 'x' axis represents time and the 'y' axis the work to be done, i.e. the CAD BOM. Time was tracked in terms of days and also hours.

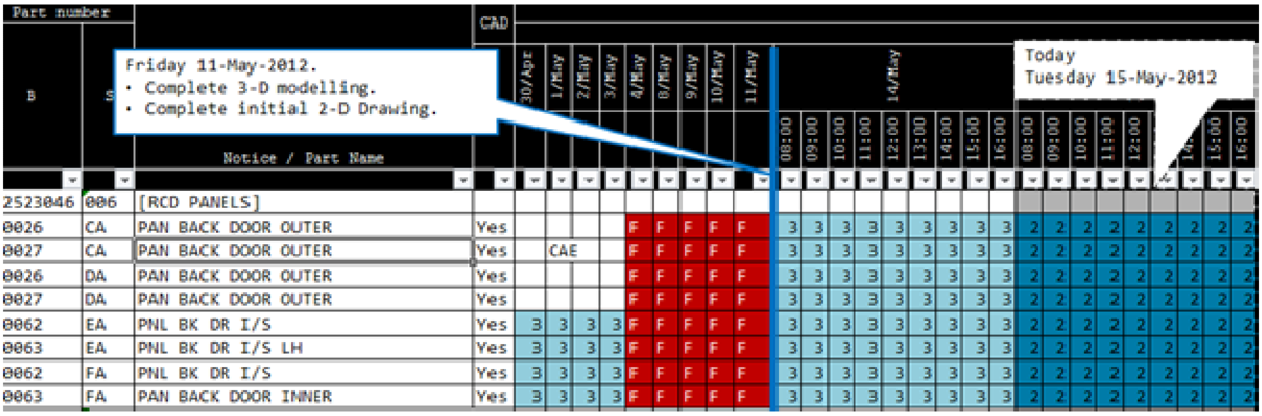


Figure 6.3.1.2 – Excel depiction of Kanban

In this phase of the project, RLE was responsible for the CAD (3D, 2D & Checking) and the OEM customer was responsible for the CAE and Manufacturing Engineering (ME) feasibility checks. The location of each CAD model on any given day is represented by a symbol in ECFD Excel model as shown in figure 6.3.1.3.

In CAE	CAE
3-D Modelling	3
2-D Drawing(GD&T, FFI, PMI, etc.)	2
Feasibility (Stamping, supplier, CAE, etc.	F
CAD Checking (annotation, CN object, etc.)	C
WACTS updates	W

Figure 6.3.1.3 – Representation of Departments in the ECFD.

In figure 6.3.1.4 the parts from the project BOM are sorted on the left and the transition between departments is shown as staggered in batches rather than angled straight lines.

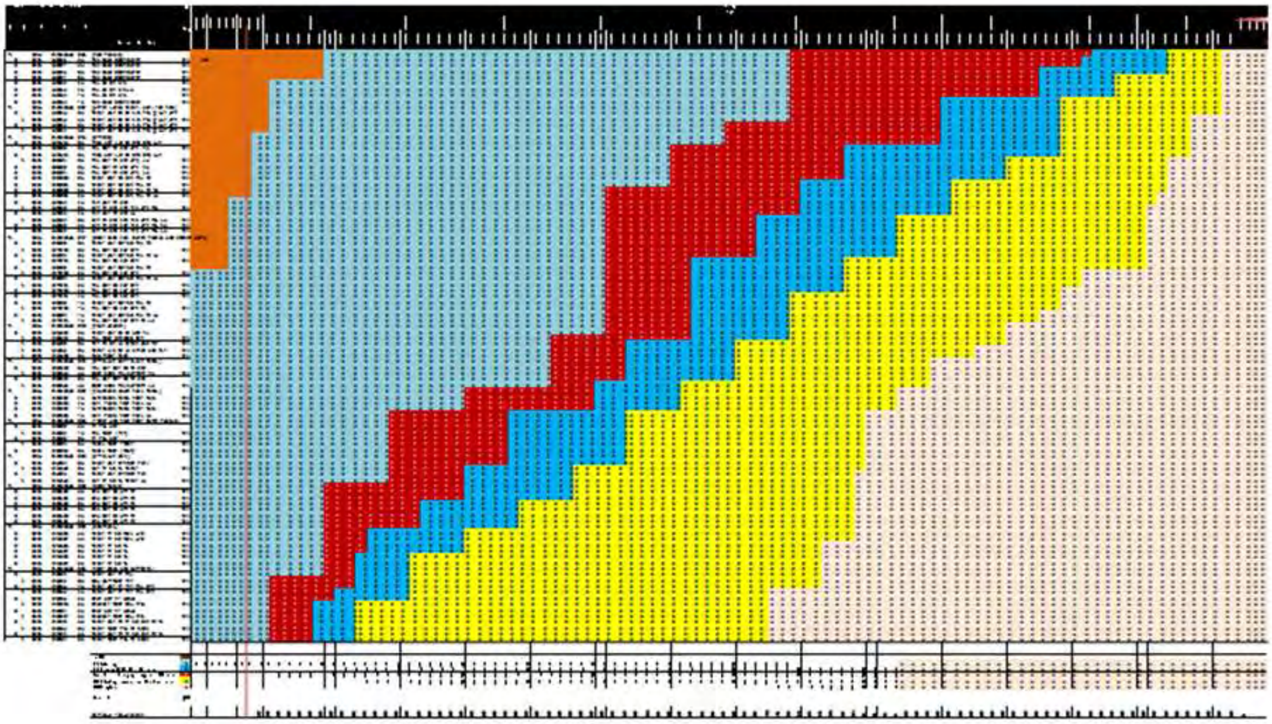


Fig 6.3.1.4 – ECFD as Implemented at RLE

The upper section of the ECFD is shown in figure 6.3.1.5. Here the timescale on the 'x' axis and the BOM on the 'y' axis are shown.

Notice / Part number				Timing 2012																										
P	B	S	Notice / Part Name	30/Apr	1/May	2/May	3/May	4/May	8/May	9/May	10/May	11/May	15/May 08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	16/May 08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
BK21	V40026	CA	PNL BDY SD EXT OTR		CAE		3	3	3	F	F	F	F	F	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W
BK21	V40027	CA	PNL BDY SD EXT OTR		CAE		3	3	3	F	F	F	F	F	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W
BK21	V40026	DA	PNL BDY SD EXT OTR		CAE		3	3	3	F	F	F	F	F	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W
BK21	V40027	DA	REINF ASY BDY SD PNL RR		CAE		3	3	3	F	F	F	F	2	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W
BK21	V40062	EA	PNL BDY SD EXT OTR RR	CAE	3	3	3	F	F	F	F	F	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W	W	W	W
BK21	V40063	EA	REINF ASY BDY SD PNL RR LH	3	3	3	f	F	F	F	F	F	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W	W	W	W
BK21	V40062	FA	PNL BDY SD EXT OTR RR LH	3	3	3	f	F	F	F	F	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W	W	W	W
BK21	V40063	FA	PAN BACK DOOR INNER	3	3	3	f	F	F	F	2	2	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W	W	W	W
BK21	V40054	AA	REINF ASY BK DR I/S PNL @ LAT UPR	3	3	f	f	F	F	2	2	2	2	2	2	C	C	C	C	C	C	W	W	W	W	W	W	W	W	W
BK21	V40055	AB	REINF ASY BK DR I/S PNL @ LAT UPR	3	f	f	f	F	2	2	2	2	2	2	2	C	C	C	C	C	C	W	W	W	W	W	W	W	W	W
BK21	V00200	BA	PNL BDY RR CNR UPR RH	3	f	f	2	2	2	2	2	2	C	C	C	C	C	W	W	W	W	W	W	W	W	W	W	W	W	W

Fig 6.3.1.5 – Upper Section of ECFD as implemented at RLE

The ECFD chart was updated on a daily basis, to display for each BOM part, whereabouts in the PD process, i.e. which department it was sitting in. This was a laborious task on this project automation will be considered for subsequent projects. Future resource levels were automatically adjusted as per the predicted information flows and workload at each department. This is shown in the lower section of the ECFD in figure 6.3.1.6.

PANEL ROOF (REAR)	Yes	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	F	F	F
REINF ASY CTR BDY PLR/	Yes	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	3	F	F	F
EXT RF SD RL REINF	Yes	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	3	F	F	F
BRA BDY SD UPR RR	Yes	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	F	F	F	F	F	F	F	F	F
REINF RF SD RAIL W/O	Yes	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	F	F	F	F	2	2	2	2	2
REINF RF SD RL	Yes	CAE	CAE	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	F	F	F	2	2	2	2	2	C
REINF ASY RF PNL	Yes	CAE	CAE	3	3	3	3	3	3	3	3	3	3	3	3	3	F	F	F	2	2	2	2	2	C
BOW ASY-ROOF FRT	Yes	CAE	CAE	3	3	3	3	3	3	3	3	F	F	F	F	F	F	F	F	2	2	2	2	2	C
REINF ASY RF FRT PNL CTR	Yes	CAE	CAE	3	3	3	3	3	3	3	3	F	F	F	F	F	F	2	2	2	2	2	2	2	C
BRKT ASY RF H/DWN	Yes	CAE	CAE	3	3	3	3	3	3	3	3	F	F	F	F	F	F	2	2	2	2	2	2	2	C
BRACKET ROOF BOW MTG.	Yes	3	3	3	3	3	3	3	3	3	3	F	F	F	F	2	2	2	2	C	C	C	C	C	C
BRKT ASY RF H/DWN	Yes	3	3	3	3	3	3	3	3	3	3	F	F	F	F	2	2	2	2	C	C	C	C	C	C
REINF ASY RR RF SD INR RR RL	Yes	3	3	3	3	3	3	3	3	3	3	F	F	F	F	2	2	2	2	C	C	C	C	C	C
REINF ROOF PNL RR SIDE	Yes	3	3	3	3	3	3	3	3	3	3	F	F	F	F	2	2	2	2	C	C	C	C	C	C
Headcount Requirement																									
In CAE	CAE	10	10	6	6	3	3	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-D Modelling	3	4	4	8	8	11	11	11	11	11	13	7	7	7	7	7	3	3	3	3	3	3	0	0	0
2-D Drawing(GD&T, FFI, PMI, etc.)	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	6	6	5	6	6	6	6	1
Feasibility (Stamping, supplier, CAE, etc	F	0	0	0	0	0	0	0	0	0	0	7	7	7	7	3	7	5	5	2	1	1	4	4	4
CAD Checking (annotation, CN object, etc.)	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4	4	4	9
WACTS updates	W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total CAD @ RLE		**4**	**4**	**8**	**8**	**11**	**11**	**11**	**11**	**11**	**13**	**7**	**7**	**7**	**7**	**11**	**7**	**9**	**9**	**12**	**13**	**13**	**10**	**10**	**10**

Fig 6.3.1.6 – Lower Section of ECFD as implemented at RLE

From this extract, it can be shown that the reinforcement to the roof assembly (Reinf Assy Rf Pnl) will remain in the OEM's CAE department for two hours before being handed over to the RLE CAD department for 3D modelling that is forecast to take 13 hours. Subsequent to this the part is planned to be transitioned to ME for feasibility assessment then back to the CAD department for 2D drawing generation and checking prior to final release into the OEM's releasing system, Worldwide Alert & Concern Tracking System (WACTS). The key predictive aspect of the ECFD is that if the part remains with CAE for a longer period the whole forecast will move the right, thus changing the WIP in each department and the CAD resource level calculation at the bottom of the chart.

In the evaluation project, resources were moved between projects to ensure the best use of resource and reduce wasted time waiting for information that would not arrive on time. The ECFD enabled RLE to meet the OEM customer's final timing plan and justified adding significant additional resource over and above that originally planned in March 2011.

Performance measurement of the ECFD can be related back to the new six point PMBOK 'triple constraint':

- Schedule
- Budget
- Scope

- Quality
- Risk
- Resources

Once applied, the ECFD was used to maintain the planned schedule, scope, quality and risk level of the project. The resource levels were adjusted throughout the remaining project period resulting in a budget over-run for the OEM customer. However, had the ECFD been adopted at the projects inception in March 2011, resource levels in the earlier stages would have been reduced as the lack of information flow and WIP would have been anticipated. The additional costs would have been avoided and ten weeks could have been taken out of the final lead time. These ten weeks, involved the utilisation of approximately thirteen engineers and designers. This led to additional revenues to RLE on this project in the first half of 2012 in excess of £300,000 (Figure 6.3.1.7).

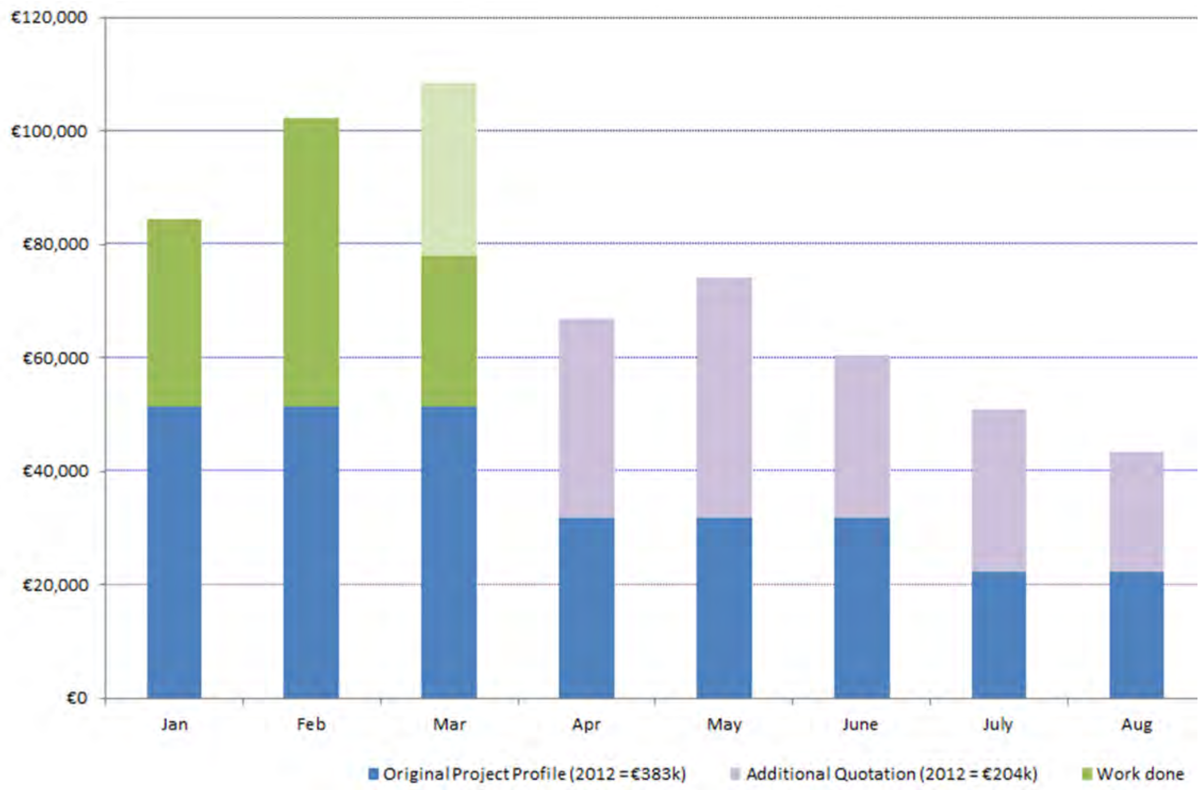


Fig 6.3.1.7 – Additional Cost of Resource (Headcount) added to the Project

The additional revenues represent the incremental resource added to the project. The main point here is that RLE had visibility of the impending increase workload and was able to react to this in a timely manner.

6.4 The Information Flow Paradigm Shift and Benefits of the ECFD

In summary, whilst existing project management tools, such as the Gantt chart, deliver a good planning tool they do not provide a real-time project control tool that predicts performance.

Similarly, the traditional KPIs of time, budget and scope are set as targets but reporting against them is lagging indicator of performance. The ECFD provides a leading indicator of project performance that predicts WIP levels and facilitates real-time resource levelling.

The ECFD assimilates a huge amount of data into one picture that enables decision makers, at both the project management and OEM corporate level, to make key judgements.

The Extended Cumulative Flow Diagram (ECFD) is unique as it covers several sub-processes and provides a broad overview of project performance. Development processes have become increasingly virtual in their approach and thus the use of physical prototype parts as an aid to understanding and communication has been lost. The use of the Extended Cumulative Flow Diagram (ECFD) enables better understanding of information flows and project progress that can be applied to many multi-step digital or virtual processes.

The ECFD is unique in that it provides:

- A planning tool that visualises multi-department WIP and enables predictive resource level requirements and cost decisions to be made.
- Considers workload and performance in prior departments and sub-processes up-stream in the overall PD process.
- Effective project control by providing a leading predictive indicator of project success or failure.

- Real-time monitoring of performance thus enabling effective modification of resource usage.
- Reduces resource overload and panic at project gateways.

Benefits include:

- Metrics to evaluate project performance internally and externally.
- Real-time control and feedback measures to drive improvement.
- Competitive advantage in the industry.

In short, this approach shifts the paradigm from reactive problem solving and retrospective action to predictive indication of departmental WIP and real time control.

It is envisaged that the application of the ECFD is transferable to other OEM and supplier PD processes irrespective of company size, culture or PD system.

6.5 Summary of Evaluation Outcomes

Project 3 of this research programme set out to identify a method that could be used for measuring or indicating information flow in the automotive PD process. This has been achieved by the use of the Extended Cumulative Flow Diagram (ECFD).

The indication and visualisation of information flow provided by the ECFD have enabled project control and feedback measures to drive improvement in performance in the automotive PD process.

7 Discussion of Information Flow Measurement in the Automotive Product Development Process

7.1 Measuring and Visualising Flow

Project 3 set out to research and identify a suitable technique that could be applied in the automotive PD process to enable better performance prediction and this improved resource allocation. The proposed method of using extended cumulative flow diagrams, adapted from the software development process, provides a simple visualisation technique that provides various performance analysis opportunities:

- Backlog
- Throughput or Cycle time
- Work-in-Progress

The applicability of this technique prescribed as it is in computer based software development is particularly valid in the virtual engineering environment widely employed in automotive PD and serves to demystify the level of project progress along the virtual value chain.

7.2 Discussion

During the evaluation of automotive PD projects in projects 2 and 3 it became apparent that whilst information flow within departments flows smoothly it is the interactions between departments where issues and delays arise.

The approach of considering handovers at interfaces and using extended cumulative flow diagrams to monitor information flows between departments has therefore been validated through application on actual live project and the organisation has benefited from the improved project performance. This demonstration has satisfied the original research programme expectation and research aims and from the research undertaken it is clear that the hypothesis is well founded. This affirmation is confirmed resolutely by the issues identified in project 2 and recognised in the case study in project 3. That is:

1 Current performance measurement techniques employed in the automotive PD process do not adequately indicate progress toward project success.
2 If information flow is not monitored and regulated in line with the project plan then company resources are wasted as they are under-utilised.

The solution developed and demonstrated in project 3 enabled the project team and its management to understand how information was flowing against the project plan and adjust resources levels as required, therefore reducing wasted time.

7.3 Implications for the Product Development and Project Management Process

The author has been involved in PD in the automotive sector for over 25 years and witnessed the development of digital processes from early CAD systems in the 1980s, through digital innovation strategies in the 1990s, e.g. Mazda's MDI (Mazda Digital Innovation) (Hino, 2006), to today's virtual development processes. The virtual value chain model (Rayport & Sviokla, 1995), figure 7.3.2, describes the benefits of virtual simulation and digital processing in a number of industries. Whilst virtual prototypes in the automotive industry have helped reduce vehicle develpment costs and project lead time, the benefits imparted to communication and understanding of the PD process are more difficult to quantify.

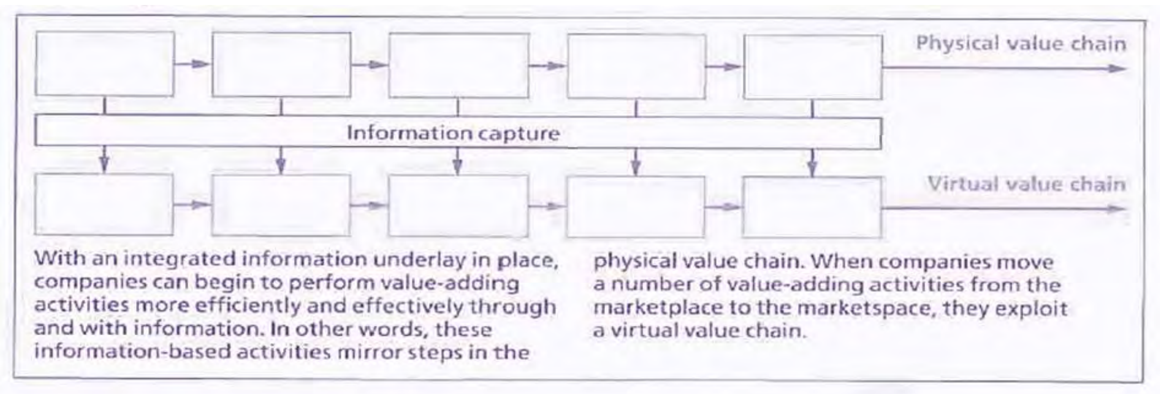


Fig. 7.3.1 – The Virtual Value Chain (source: Rayport & Sviokla, 1995)

Whilst the digital process has helped reduce cost (e.g. number of physical prototypes) and helped facilitate the adoption of the simultaneous engineering process to reduce process time from Kick Off (KO) to Engineering Sign Off (ESO) (figure 7.3.2), issues have been identified in that that the lack of physical properties leads to a situation where it is difficult to visualise progress.

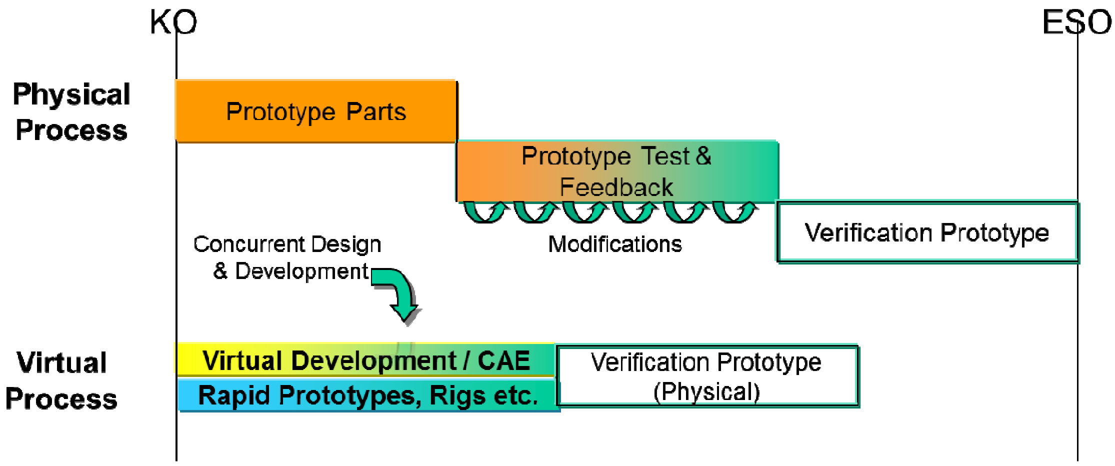


Fig. 7.3.2 Physical Prototype Process vs. Virtual Process (source: RLE)

7.4 Business Implications

Competitive advantage can be attained by RLE by use of the ECFD. This will provide a powerful marketing opportunity as the company seeks to develop further project business.

However, RLE needs to implement a global Project Management Office (PMO) to provide a central role in controlling its approach to project management. The current approach with different techniques adopted in the various offices is too fragmented and does not portray a coherent global organisation.

7.5 Discussion of the Broader Implications of Understanding Information Flows in the Digital Enterprise

Virtual engineering or Digital Innovation (DI) as it has also come to be known at several OEMs has accelerated the automotive PD process. The 3D geometry created in the PD process is now essential to many OEMs processes including those beyond the PD department, figure 7.5.1.

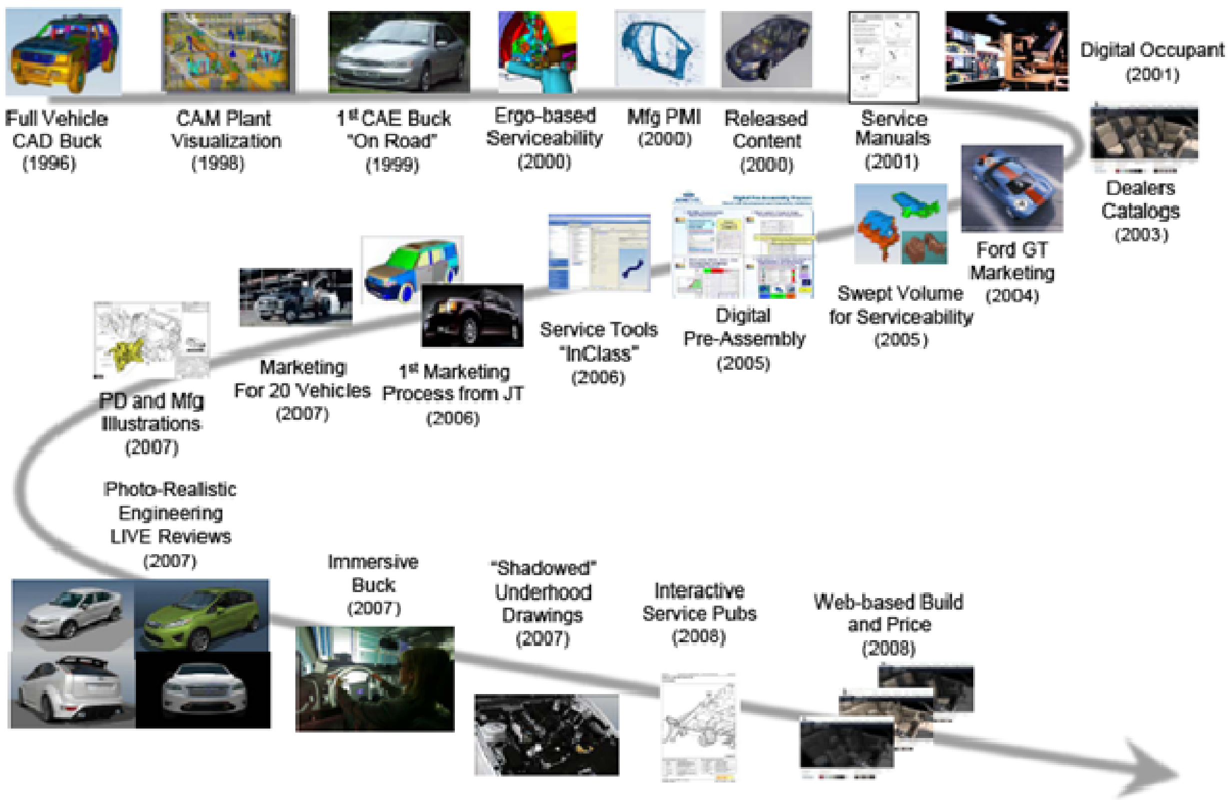


Figure 7.5.1 – Applications of Data in the Digital Enterprise

(Adapted from: Riff, 2010)

8 Conclusions

Project 3 of this research programme set out to identify a method that could be used for measuring or indicating information flow in the automotive product development process.

The validity of using cumulative flow diagrams in the automotive PD process was demonstrated on the same, now re-timed, project that was studied.

The application of the Extended Cumulative Flow Diagram (ECFD) was explained to the RLE project team and its use extended beyond just considering local department work-in-progress and backlog queues. This approach allowed the project's management to foresee future workloads and adopt control and feedback measure to drive improvements in project performance.

The objectives of this research programme have been achieved. The three research projects have confirmed that there is an issue in the automotive PD process, isolated one of the root causes, proposed a unique solution and validated this on a live project. Moreover, the simplicity of the solution facilitates its transferability to other automotive OEM PD systems and indeed to PD processes in other industries.

9 Recommendations for Future Work

This work has achieved its objectives but areas of further work can be highlighted. Recommendations are given to define key issues for possible continuation of the research into the use of flow measurement as a key characteristic of successful product development.

Future research requirements into flow in the PD process have been recognised (Martinez Leon & Farris, 2011). The research programme has established that information flow measurement is a key characteristic of successful PD. The application to larger development projects and with different OEMs needs to be further evaluated.

The automotive industry OEM PD processes have evolved over several years and a full assessment involving Value Stream Mapping and/or Design Structure Matrices would be a large piece of research work but one that may lead to fundamentally new approaches. Maybe even a truly agile design of development process.

Whilst the cumulative flow diagram is used in software development it could be applied in many PD processes in other industries. Indeed, not just PD, but any multi-stage digital process.

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