INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

A METHODOLOGY FOR EVALUATING TECHNOLOGY READINESS DURING PRODUCT DEVELOPMENT

Ben Hicks[1], Andreas Larsson[2], Steve Culley [1] and Tobias Larsson[2]
(1) University of Bath, UK (2) Luleå University of Technology.

ABSTRACT

In today's highly competitive global markets, where products are driven by rapidly advancing technologies and the ever-increasing expectations of the customer, robust methods for identifying new technologies and assessing their suitability and readiness within the context of the product development process are essential. Despite this fundamental requirement there are few supportive techniques available, with the exception of the nine Technology Readiness Levels developed by NASA. However, the generality and suitability of this approach is somewhat limited for the purpose of supporting product design and development. To address this, the existing NASA model has been critically appraised and its generality enhanced. The more general model has also been extended to consider the technology lifecycle (i.e. further refinement and development), multi-tech products and the associated criticality of each technology. The extended model of the Technology Readiness Level of the Product (TRL_{PROD}) is then contextualized with respect to the product development process in order to provide a methodology for assessing the Product Readiness Levels (PRL). The paper describes the key stages of methodology development and illustrates the approach through consideration of the case of Liquid Crystal Displays (LCD).

Keywords: technology management, technology lifecycles, product development, product design

1 INTRODUCTION

In today's highly competitive global markets, where products are driven by rapidly advancing technologies and the ever-increasing expectations of the customer, robust methods for identifying new technologies and assessing their suitability and readiness within the context of the product development process is essential. A failure to effectively monitor and measure technology readiness can result in significantly increased business risk, extended product development time, a poorly performing product – in terms of quality, function and performance – and in extreme cases failed development programmes and potentially serious commercial implications [1, 2].

The importance of technology for an organisation's commercial success is widely acknowledged [2, 3, 4] and a number of approaches to support technology management have been researched. These include Technology Intelligence, Portfolio Methods and Technology Forecasting. Technology Intelligence also known as Competitive Intelligence (CI), involves the capture and delivery of technological information as part of the process whereby an organization develops an awareness of technology threats and opportunities [3]. In contrast to CI, Portfolio Methods are designed to generate a snapshot of an organisation's technological capability and their significance to the business. This process typically involves identifying those technologies that are both important to the future sustainability of the organization and those which could threaten the existing technology base (sustaining and disruptive technologies) [4]. The third approach, Technology Foresight or Technology Futures Analysis, considers the trajectory of technology development and the anticipated impact that it will have on an organisation's commercial success [5]. This will typically involve the Delphi approach (bringing together expert opinions in a structured manner), scenarios that amalgamate various forecasts and extrapolation approaches, using historical data and the assumption that technology develops along a predetermined path – what is referred to as the s-curve. In addition to approaches which are explicitly focused on technology itself there exist a range of paradigms that deal with technology and innovation management within the context of the wider business, marketing and economics [6, 7]

Whilst these approaches are all important for understanding and increasing technology awareness as well as strategic decision-making, none of the approaches can be considered to support technology assessment within the context of accepted models of the product development process. That is to say, the approaches do not provide an indication of the suitability or level of development required, effectively the readiness, of a technology for incorporation into a new or existing system. One of the few approaches that does provide an objective measure of technology that is contextualized with respect to the engineering activity – albeit based on qualitative assessment – is the widely used nine stage technology readiness model developed by NASA [8].

However, this approach is somewhat limited in terms of its generality and suitability for the purpose of supporting product design and development within hi-tech, consumer goods and advanced engineering manufacturers. Within these sectors product development and advancement depends on a multitude of factors, including new and emerging technologies, as technological leadership is often a key product differentiator. In addition to the need for manufacturers to leverage and incorporate new technologies, in the advanced engineering sectors, such as medical devices and security, products are highly complex and safety-critical, and product volumes are very low. As a consequence of these factors product development programmes can span many years and involve a large number of specialists and suppliers, and hence represent a significant level of uncertainty and business risk. It is generally accepted that the monitoring, management and control of such programmes and their risks is largely dependent upon suitable means for assessing progress - what can be thought of as readiness.

It is the challenge of relating technology readiness to the product development processes that is addressed in this paper. The paper begins by critically appraising the scope of the National Aeronautics and Space Administration (NASA) model, and then proposes a revised set of Technology Readiness Level (TRL) definitions. The NASA nine stage model is then extended to reflect the technology lifecycle (i.e. further refinement and development). This extended model is then contextualized with respect to the product development process as proposed by Ulrich and Eppinger [2]. The paper describes the key stages of methodology development and uses the case of the Liquid Crystal Display (LCD) as an exemplar.

2 A GENERAL MODEL OF TECHNOLOGY READINESS LEVELS

The concept of 'technology readiness' was first conceived by NASA during the 1960s [8]. They required a means of relating the development status of a prospective system's technology to the desired level of 'flight readiness' – a term synonymous with aeronautical development throughout industry and the armed forces. In the following decade this concept was formalised into a qualitative measure of technology maturity for multivolume space systems-technology models – 'Technology Readiness Levels' [8]. The advent of these metrics, which further provided information on new system concepts or applications, performance data, and technology needs, provided a valuable tool for communication between the research and development (R&D) department and those involved in both ongoing and proposed flight projects. The concept of these metrics was to later influence the formulation of a broad template for technology assessment and R&D coordination both within NASA and throughout other related organisations [8]. In 1995, John Mankins expanded the NASA TRL definitions from the seven levels, originally put forward by Sadin et al (cited in [9]), to the nine levels now taken as the benchmark descriptions upon which other organisations have proceeded to form their own measures. Full descriptions and example scenarios are given in [10] whilst the nine TRLs are summarised in Figure 1.

2.1 Limitations of Technology Readiness Levels (TRLs)

Despite their continuing adoption by multinational corporations, concerns have been expressed regarding the credibility of TRLs as a generic indicator of technology advancement [11]. Whilst TRLs were predominantly used within NASA to support maturity assessments and comparisons between different hardware technologies, the Department of Defense (DoD) has shown great interest in expanding their application to provide risk assessments for full systems incorporating both hardware and software. However, increasing numbers of sources have cited the difficulties in applying TRLs to assess the readiness of technologies and products that are primarily software-based [11]. As it turns out, studying the merits of TRLs in assessing software-based developments provides a useful analogy for any multi-technology system that requires evaluation and assessment of its project risks. This is because software is typically developed for use within a larger software-intensive system for a particular purpose or application.

Some of the key limitations identified by Smith [11] include 'blurring' where various characteristics of the item under development contribute towards achieving a given TRL. In such instances it becomes extremely difficult to understand the influence of any one aspect towards the TRL, and thus where further development efforts are needed. Product 'criticality' is equally significant as no account is made of the degree to which the technology is critical to the overall success of the product, nor in fact the suitability of the technology under development to its intended application - an aspect very relevant to technology making the transition from one domain to another. This is an issue also noted by Mankins [8], who proposes the 'Technology Need Value' and differentiates contributing technologies on a numerical scale by their criticality to the functional characteristics of the complete system (i.e. full product) and the ease with which a work-around, or substitute technology, can be obtained.

In addition to the issues concerning the embodiment of multiple technologies in products, 'ageing' is also identified as an issue. For example, in the case of software which typically receives regular upgrades the standard NASA-derived TRL metrics would remain at a level of nine irrespective of any future upgrades, refinements or product modifications. This inability to reflect the product lifecycles and arguably the technology lifecycle is in stark contrast to the emerging philosophies surrounding lifecycle management [12].

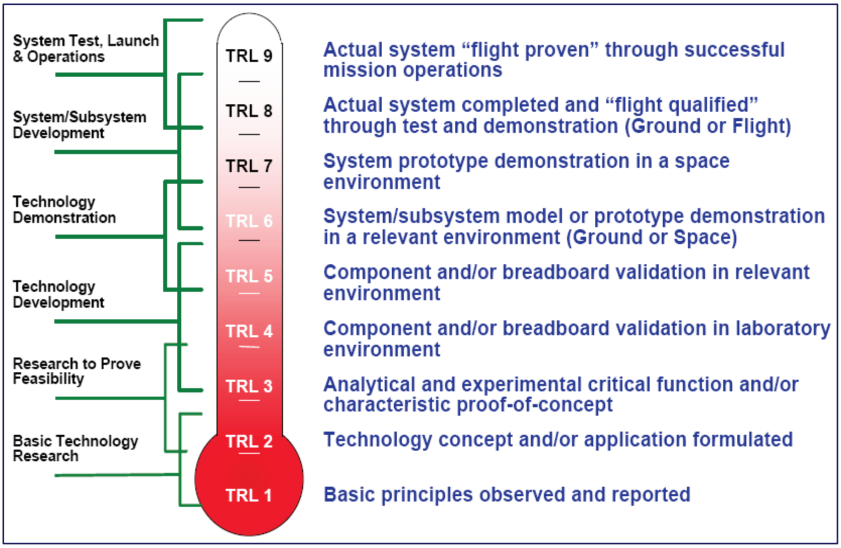

Figure 1. Existing model for Technology Readiness (NASA)

While much of the documentation surrounding TRLs (including the NASA definitions) use the terms 'readiness' and 'maturity' interchangeably, there is in fact, an important distinction to be made. In the context of a specific application, a mature product may possess a greater or lesser degree of 'readiness' than one of a lower maturity. The 'readiness' of a technology can only truly be assessed against a specific requirement, often a functional task which that technology has to accomplish. This permits some measure of the risk associated with using the technology for that particular application, i.e. the higher the TRL, the lower the overall risk. However Smith [11] points out that the very aspects of a technology's readiness that can result in 'blurring' (functionality, maintainability, reliability, etc) of how each characteristic contributes to the overall TRL in varying degrees and at different times throughout the development program.

In summary, there can be considered to be four fundamental limitations to the existing nine level technology readiness model. These include:

1. An inability to assess **multiple technologies**, i.e. how do the individual parts affect the whole?
2. A lack of consideration of the **criticality** of each technology, i.e. which parts can be safely substituted?
3. An inability to assess the **applicability**, i.e. how does the technology under development suit its intended application context?
4. A lack of consideration of **life-cycle** aspects, i.e. what happens with the readiness as the product is modified or competing technologies become more mature? Do we downgrade the TRL, and for what reasons?

It is these fundamental issues which are addressed in this paper. However prior to addressing these, the issue of generality is first considered. In particular, the existing TRL definitions were generated for a particular industry (space/aerospace) and context (flight readiness) which demanded that both technology (TRLs 1-5) and systems/products (TRLs 6-9) were represented in the same model. To overcome this, a generalised definition of technology readiness is developed.

2.2 A generalised definition of technology readiness levels

TRL	Definition
1	Principal research into the core properties of a technology.
2	'Invention' of a concept or application for the technology. Shift from principle to applied research.
3	Initial 'proof of concept' of critical functionality through active R&D (Analytical and laboratory studies in appropriate context to validate previous analytical predictions)
4	Low-fidelity validation in laboratory environment. Technological advancement now focussed on meeting project requirements.
5	Validation of basic technological elements in a relevant environment. Test 'set-up' to be of higher fidelity than at TRL 4.
6	High-fidelity 'alpha' prototype demonstrated in a relevant environment.
7	'Beta' prototype (Of appropriate or full-scale) demonstrated in an operational environment.
8	Completed component, sub-system or system qualified to relevant project requirements and/or regulatory standards.
9	Certified component, sub-system or system proven to meet all project requirements through 'real world' operation.

Table 1. Generalised definitions for Technology Readiness Levels

While research continues to address how best to overcome the limitations of TRLs, by proposing varying developments. This inevitably leads to more complex and time-consuming methodologies. This is a significant drawback, as to be readily adopted by an organisation a solution methodology must integrate neatly with the common work practices of the employees. As such, developing more sophisticated, albeit accurate, methods for evaluating and assessing TRLs could become a redundant measure if the efforts required for the application of that method outweigh the benefits of the TRL metrics.

With this in mind, the work reported in this paper focuses on extending the generality of the existing TRL approach. The first stage in this process is to develop the existing nine levels definitions into more generalized descriptions that are independent of industry and largely technology based – rather than product or domain based. This revised set of definitions is given in Table 1.

3 THE TECHNOLOGY LIFECYCLE

As previously stated, the existing TRL scheme only represents the initial R&D and does not capture further development and diversification of technologies. In order to address this shortcoming a technology lifecycle model (Figure 2) is adopted based upon the logical combination of existing technology, product, and marketing models [2, 13, 14]. Of particular importance is the requirement to identify the transition point from the 'New Invention' phase to the 'Technology Improvement' phase. For the purpose of extending the existing TRL model, this transition point naturally occurs once a product has achieved a TRL of 9 and has successfully been launched into the marketplace, identified by 'B' in Figure 2. Whilst the developing organisation will obviously be aware of the success in developing the contributing technologies, those outside of the industry for whom the technology may represent a potentially disruptive or sustaining force within their own market might not be aware of its successful development (particularly if it only forms a component or sub-system within the product).

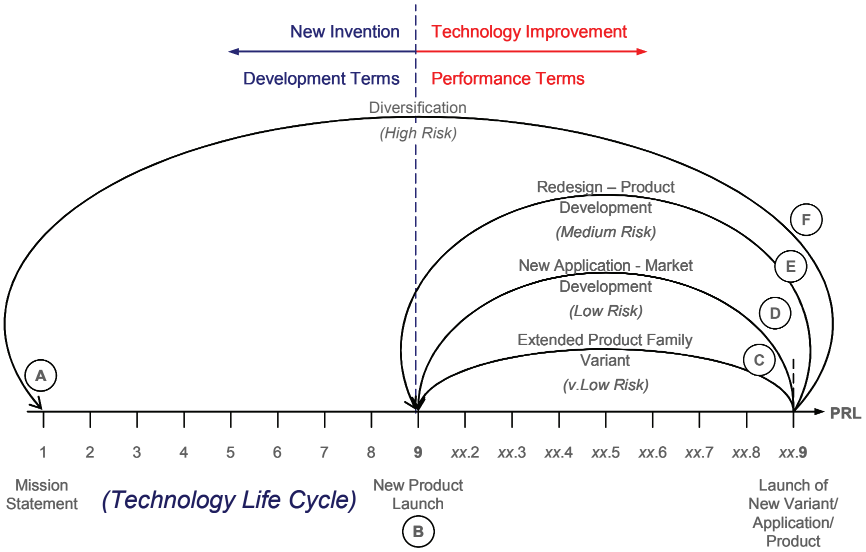

Figure 2. The Technology Product Lifecycle Model

Beyond this transition to 'Technology Improvement', Figure 2 shows the cyclic nature of further technological development. Initially the low risk options of extending the product family with new variants (C) and identifying new applications for the product's core function (D) are explored. Here the numbering system of the TRL framework identifies these additional product models and goes as far as to include the 'Product Development' stage (E), where a new product family is required based upon developments to the existing technologies. This iterative cycle then continues until obsolescence or diversification (F). While the latter is the most high-risk of the strategic choices available to an organisation, it is an inevitable and essential step for continued survival within a competitive environment. For the purpose of representing and capturing these iterative improvement cycles (C, D and E) technology readiness levels 10 and 11 are introduced (Table 2). These levels and in particular level 10, comprise sublevels that are derivative to TRLs 2-9 and reflect product improvement. Importantly, for the purpose of product development there exists no level 1 as the technology is already existent and is therefore subject to improvement rather than fundamental R&D.

TRL	Definition
10.2	The enhancement of an existing element or the introduction of a 'sustaining technology' to an already operational component, sub-system or system is conceived. Commencement of applied research.
10.3	Feasibility and key benefits of enhancement or introduction initially validated through active R&D (Physical validation and analytical study of technology in appropriate context)
10.4	Low-fidelity validation of new 'feature' in a laboratory environment. Technological implementation now focussed on meeting project requirements.
10.5	Validation of new 'feature' in a relevant environment. Test 'set-up' to be of higher fidelity than at TRL 4 (Basic integration of new 'feature' with established components required for a sub-system or system).
10.6	High-fidelity 'alpha' prototype of (Or incorporating) new 'feature' demonstrated in a relevant environment.
10.7	'Beta' prototype (Of appropriate or full-scale) demonstrated in operational environment (New element must be fully integrated with established components for a sub-system or system).
10.8	New 'feature' qualified to relevant project requirements and/or regulatory standards.
10.9	Revised and certified component, sub-system or system proven to all governing meet requirements through 'real world' operation.
11.2	The enhancement of an existing element or the introduction of a 'sustaining technology' to an already operational component, sub-system or system is conceived. Commencement of applied research.
11.3	*Continue TRL progressions as before…*

Table 2. Extended Technology Readiness Levels to include further development

3.1 Case study - LCD

In order to evaluate the proposed technology-product life cycle the case of the Liquid Crystal Display (LCD) is considered. Bibliometric techniques were used determine the publicised history of LCD technology. The motivation behind taking this approach is the apparent relationship between the "R&D Profile" and "Technology Life Cycle Indicators" put forward by Watts and Porter [13]. In essence, this surmised that as a technology develops from fundamental research through to mainstream application, the source types reporting on its advancing status would also progress from academic databases through to patents, the trade press, and then finally the popular press. The results are shown in Figure 3.

In addition to the bibliometric data, the historical development of LCD technology was also researched. This focused on both the initial scientific research leading to the first operational display and then the subsequent technological developments and commercial offshoots that were influential in transforming LCDs into a major global industry. The historical developments were extracted from 'The History of Liquid-Crystal Displays' [15], which tracks the efforts of the LCD industry and in particular the Sharp Corporation, to produce the first thin, full-colour, wall-mountable television display. This was finally achieved in 1991, a quarter of a century after the initial concept was formed by George Heilmeier at RCA Laboratories. Along the way it details the development of the major products that were responsible for 'kick-starting' the LCD industry, namely digital watches and pocket calculators, through to the early black and white and monochrome displays used for personal computing devices in the mid-to-late 1980's.

Following the chronological review of LCD development, the dates of significant technological breakthroughs and major commercial product launches were mapped to the plot of the collated source data in Figure 3. The key technological-product developments are clearly identifiable and include:

- The launch of new products (B)
- The development of variants to that product family (C) (Sharp TN-mode calculator in 1976)
- The 'Market Development' of SM LCD displays into a host of different products (D) in the mid 1980s.
- A major 'Product Development' in 1991 (E) - the advent of Sharp's full-colour wall hanging AM TFT-LCD TV represents a major performance improvement over the previously small-scale colour displays.

Since the LCD case represents the entire industry and not a specific technological subset, the points at which new products were launched (B) do not coincide with the overall transition to the 'Technology Improvement' phase of its maturity profile (Although if only large-size full colour AM TFT-LCD displays are considered then the launch of Sharp's TFT-LCD in 1991 represents such a transition).

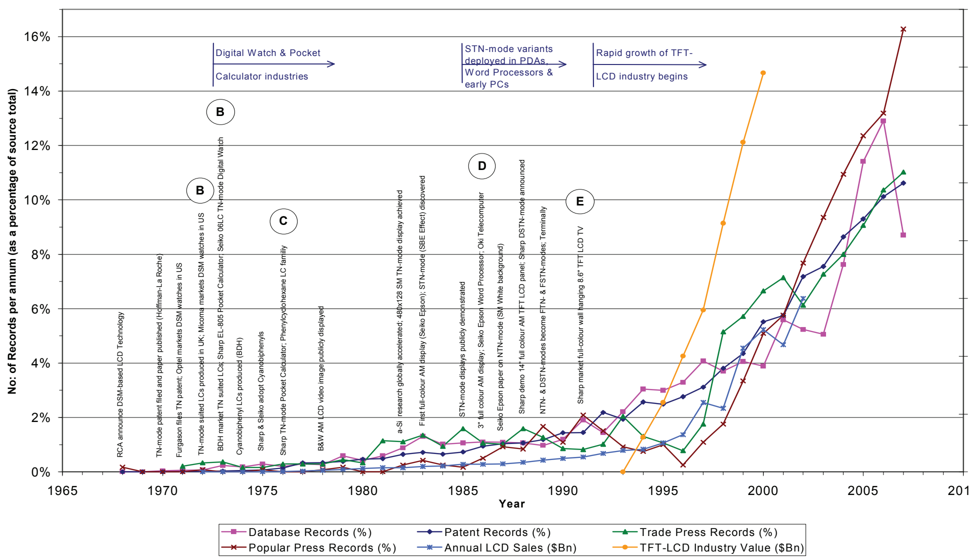

Figure 3. The key technology lifecycle events for LCDs

4 PRODUCT DEVELOPMENT (MULTI-TECHNOLOGY)

It was also stated in the critique of the nine level NASA TRL framework that there is no clear distinction between the, very often, multiple technologies that provide the basis for a product. It was further identified that if multiple technologies are to be considered there is a need to assess their criticality with respect to realising the final product. The implications of this would be for example, that a program manager using the existing TRL framework could not account for the significance of an external disturbance, such as a technology failing to mature or a supplier backing out of their contract. This is due to the fact that no account was made of how critical each contributing technology was to the overall product/system's core functionality.

To overcome this, a measure of technology readiness level is proposed that is based on three levels of criticality. These are given in Table 3 and are inspired by Mankins' 'Technology Need Values' [8]. This is complemented by a normalised TRL measure which has been developed to enable a single TRL value to emerge for a project by considering each of the key contributing technologies and their respective criticality to the realisation of the product. This measure is termed the 'Technology Readiness Level of the Product' (TRL_{PROD}) and is calculated in the following manner:

1. List all of the technologies that contribute to the product's functionality.
2. Assign them each a TRL according to previous guidelines in Section 3.
3. Assign each technology with a 'Criticality Value' as defined in Table 3.
4. Multiply the TRL of each technology by its 'Criticality Value'.
5. Divide the sum of the above products by the sum of the Criticality Values to obtain TRL_{PROD}.

Criticality Value	Definition
3	Technology is 'enabling' to the core functionality of the product. No work-around or substitution possible.
2	Technology fulfils a vital role in the product's core functionality. However, a work-around may be possible using substitute technologies that will incur an acceptable penalty.
1	Technology is 'enhancing' to the product's performance, cost, etc. Several alternative technologies exist that could be substituted and incur a minimal penalty.

Table 3. Technology criticality

$$\Rightarrow TRL_{PROD} = \frac{\sum (TRL \times Criticality)}{\sum (Criticality)}$$

Equation 1. Technology Readiness Level of Product

Essentially, the criticality measure provides a weighted average biased toward the core technologies. Consider, for example, a product that combines three technologies; T_1, T_2 and T_3 at technology readiness levels of 1, 5 and 9 respectively. In the case where T_1 is the core technology and T_2 and T_3 are vital and enhancing respectively, then the TRL_{PROD} is:

$$TRL_{PROD} = \frac{(1\times 3)+(5\times 2)+(9\times 1)}{3+2+1} = \frac{22}{6} = 3.67$$

In contrast, if T_3 is the core technology and T_2 and T_1 are vital and enhancing respectively then the TRL_{PROD} is:

$$TRL_{PROD} = \frac{(1\times 1)+(5\times 2)+(9\times 3)}{3+2+1} = \frac{38}{6} = 6.33$$

The above example illustrates the significance of considering the criticality of technology. While the principles are demonstrated through the use of simple incremented values (1, 2 and 3) greater relative weights could be applied - although appropriate justification would be necessary, which is not within the scope of this paper.

5 PRODUCT READINESS LEVELS

In addition to overcoming the limitations identified in Section 2.1, this paper also seeks to establish the relationship between technology readiness and the product design and development process. To address this, the TRL_{PROD} levels are contextualised with respect to Ulrich and Eppinger's generic product development process [2] and key business functions. The resultant framework is illustrated in Figure 4. Although the framework lists tasks performed by various aspects of a business such as research, finance, legal, sales, and field service/product support, it centres on the marketing and manufacturing functions as these, along with design (or technical development) are key aspects of the product development process.

PRL	TRL_{PROD}	Marketing	Manufacturing	Other Functions	Development Phase
1	2	• Target market identified.	-	• Business goals of development effort defined.	*Mission Statement*
2	3	• Market segments defined. • Lead users & their needs identified. • Competing products analysed.	• Manufacturing cost estimated. • Production feasibility assessed.	• Single concept selected for further development. • Project justified economically. • IPR issues investigated.	*Concept Development*
3	4	• Plan for product options and extended product family formulated.	• Make-or-Buy analysis performed. • Key suppliers identified. • Final assembly scheme designed.	• Support Make-or-Buy analysis. • Potential service issues identified.	*System-Level Design*
4	5	• Marketing plan developed.	• Standard parts identified. • Production processes defined. • Tooling designed. • Long lead-time tooling procured. • Quality assurance processes defined.	• Control documentation issued.	*Detail Design*
5	6	• Promotion and launch materials developed. • Field-testing facilitated.	• Supplier 'ramp-up' facilitated. • Fabrication and assembly processes refined. • Commence work force training. • Quality assurance processes refined.	• Sales plan finalised. • Regulatory approval / certification obtained.	*Testing and Refinement*
6	7				
7	8				
8	9	• Early 'production ramp-up' products placed with preferred customers.	• Work force training completed. • Operation of entire production system commenced.	-	*Production Ramp-Up*
9	9	*Product Promotion*	*Full Production*	*Active Service & Support Infrastructure*	*Product Launch*

Figure 4. Product Readiness Levels and the product development process

The combination of all of these essential functions into one simple framework provides project managers with a more general approach to better identify any bottlenecks in the development process and to aid communication and thus cooperation between all of the business functions concerned. Additionally, it provides executive managers with a minimalist 'product launch check-list'. For this purpose a set of nine Product Readiness Levels are mapped directly to the TRL_{PROD} levels 2-9 and the final stage of product launch.

5.1 Case study – LCDs revisited

To provide further insight into the proposed approach for determining TRL_{PROD} the case of the LCD is revisited. In particular all of the contributing technologies for the first pocket LCD calculator are identified [15] and their TRLs assessed in order to derive the Technology Readiness of the calculator. Whilst a degree of judgment was required owing to the lack of specific dates for each event, the ability to assess each technology independently, and not having to treat them as a whole as with the existing approach, enabled a consistent method to be applied for each technology assessment.

Technology	TRL	Criticality	TRL × Criticality
LC Materials	3	3	9
Pre-alignment of LCs in 1 Direction	3	3	9
Glass Plate Separation	4	3	12
'Clocked' CMOS Driving Circuits	4	3	12
Transparent & Conductive ITO Plate	6	2	12
LSIs onto Glass Substrates Process	7	2	14
Photolithography technology	3	3	9
		19	**77**

$$\Rightarrow TRL_{PROD} = \frac{\sum(TRL \times Criticality)}{\sum(Criticality)}$$

$$\therefore TRL_{PROD} = \frac{77}{19} = 4.05 \text{ or } TRL_{PROD} = 4$$

Table 4. Technology Readiness Level of the Sharp Elsi Mate EL-805 LCD Pocket Calculator at the beginning of the development process in 1970

PRL	TRL_{PROD}	New TRL Definitions	Ulrich & Eppinger (1995): Design Details	Development Phase
1	2	'Invention' of a concept or application for the technology	*Provide a basic functional description of the product*	*Mission Statement*
2	3	Initial 'proof of concept' of critical functionality through active R&D	*Investigate feasibility of product concepts*	*Concept Development*
3	4	Low-fidelity validation in laboratory environment	*Define major sub-systems and interfaces*	*System-Level Design*
4	5	Validation of basic technological elements in a relevant environment	*Define part geometry; choose materials; assign tolerances*	*Detail Design*
5	6	High-fidelity 'alpha' prototype demonstrated in a relevant environment	*Reliability, life, and performance testing*	
6	7	'Beta' prototype demonstrated in an operational environment	*Reliability, life, and performance testing*	*Testing and Refinement*
7	8	Completed system qualified to relevant project requirements and/or regulatory standards	*Obtain regulatory approvals*	
8	9	Certified system proven to meet all project requirements through 'real world' operation	*Implement design changes*	*Production Ramp-Up*
9	9	Certified system proven to meet all project requirements through 'real world' operation	*Evaluate early production output*	*Product Launch*

Table 5. Product Readiness Levels and the Design and Development Process

Taking the pocket calculator's TRL_{PROD} value of 4 at the beginning of its development and contrasting it with the PRL framework and product development process given in Table 5 (note: in Table 5 other business functions given in Figure 4 are omitted). According to the framework, the calculator would be entering the 'system-level' design phase, which correlates well with Kawamoto's paper [15].

6 CONCLUSIONS

The importance of new technology for the commercial success of engineering organisations and their products has been discussed. The need for robust methods which support the identification of new technologies and the assessment of their suitability and readiness within the context of the product development process has been established. This is particularly the case for hi-tech, advanced engineering and consumer goods where development programmes are complex; involving numerous technologies and spanning many years, and in fact represents a significant level of uncertainty and business risk. Despite this fundamental need there are few supportive techniques available which afford a quantitative assessment of technology and readiness, and more importantly product readiness. The exception to this is the nine level technology readiness model developed by NASA. However, the generality and suitability of this approach is limited beyond the domain of aeronautics and associated supporting product design and development programmes. In order to explore these limitations and overcome them the existing NASA model has been critically appraised. This appraisal revealed a number of limitations:

- It is not possible to consider multiple-technologies in a holistic manner.
- There is no consideration given to the criticality of particular technologies.
- There is no consideration of the applicability of a technology for its intended application
- There is little consideration of life-cycle aspects i.e. once a TRL of nine is achieved further development and refinement cannot be captured in the framework.
- The existing Technology Readiness Level (TRL) definitions are too focused on a particular domain and blur technology and products together.

In order to address these limitations the existing framework has been generalized and extended to incorporate the product development process. To achieve this, the TRL definitions have been expanded and the framework extended to consider the technology-product lifecycle (i.e. further refinement and development). Further, an approach for combining multiple-technologies and their criticality has been proposed and the extended model contextualized with respect to the product development process. The approach is illustrated throughout by considering the case of the LCD which shows a strong correlation between the product readiness levels determined using the extended TRL method and the history of the development of the LCD.

The proposed methodology for evaluating technology readiness and what is referred to as product readiness, provides an important step towards the creation of methods that support the assessment of product readiness during the development process. For the case considered in this paper the proposed methodology correlates well with the historical development of the LCD. However, as with the application of all methods that possess a forecasting element (in this case emerging technologies) their application necessarily incorporates a certain level of subjectivity. In the application and validation of this methodology one of the main challenges faced concerned the decomposition of a product – such as the LCD – into its constituent technologies. Clearly, this task requires an intricate knowledge of the final product and the technologies under development. As a consequence, a historical and well-understood case was considered. The next step in this research is to consider the appropriateness and usefulness of the proposed approach within a commercial environment and a New Product Development programme.

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Contact:
Ben Hicks
Department of Mechanical Engineering
University of Bath
Bath, BA2 7AY
United Kingdom
Tel: +44 (0)1225 386881
E-mail: b.j.hicks@bath.ac.uk
Web: http://www.bath.ac.uk/idmrc