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CLASSIFICATION OF TECHNOLOGY FORECASTING METHODS: STRENGTHS, WEAKNESSES AND INTEGRABILITY ANALYSES

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Abstract
This document presents a study of the most popular technology forecasting (TF) tools. Analysis of the fields of application of the TF tools along with the strengths and weaknesses have been recorded. A 4-stage model has also been proposed borrowing some features of the tools thus far studied. The tools were compared against criteria required for the development of the technology roadmapping tools in manufacturing technologies.

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1. Introduction

The study of the implicit strengths and weaknesses of technology forecasting (TF) methods and their integrability with each other demands a closer inspection of some of the techniques included in the report by M. Slupinski [1]. The motivation for this study is the need to dig deeper into some of the established TF techniques to gain insights into questions required at the start of a TF activity. Another perspective, which is considered in this task, is to learn from past experiences in using TF tools. The main motivation in this study is to answer the following questions:

1) What recommendations and warnings can be extracted from the TF tools specifically for the manufacturing systems or industries?
2) How to reliably extract knowledge from experts in a particular technology domain without introducing a bias or being influenced by the intrinsic bias of the experts?
3) How to build an intricate model with all the relevant details that is apt for forecasting technology and does not require time to build such model?

Apart from answering these questions, there is also a need to identify any other attributes or questions deemed necessary for the forecasting of technology. Since the focus of the FORMAT (FOrecasting and Roadmapping for MAnufacturing Technologies) project is on manufacturing technologies, the relevance of the selected tools specifically for manufacturing technologies gains a higher priority in the study. In this report, manufacturing technologies refers to any activity that leads to a product/service or results in a process for the development of the product/service. This deeper study is the direct result of the requirements of the FORMAT project: to provide with a tool for decision making the Research and Development (R&D) managers in order to enable them to choose the path forward.

1.1. Knowledge Extraction from Experts

Before dealing with the topic of how to extract knowledge from experts and how to deal with biases present in their opinions, there are a few basic questions that need to be answered:

Who are experts?

In the context of knowledge extraction, experts are looked at as people with information about the technology of interest to the forecaster. These experts are selected basing on a number of criteria – number of publications, years of experience, area of expertise, membership of professional bodies, reputation (measured by number of recommendation from other experts) and geographical coverage [2–5]. This list of criteria neither is an exhaustive list, nor is necessary to include all criteria in the selection process. The selection criteria seem to be dependent on the project at hand. For example, geographical coverage may be necessary when considering a global new product introduction and may be unnecessary if the project is local in nature.

When do we need experts?

With the advent of faster computers and relatively readily available published information, the next question to consider is the time of need for experts' opinion. Lack of quantifiable data from patent databases or scientific literature, the relative slowness of publication of above-mentioned sources of information vis-à-vis, the rate of change of technology and the need of subjective opinion are some of the factors that determine the timing of the need for experts' opinion. Committees and the expert panels have advantages over face-to-face meeting because "two heads are better than one" [6–8]. Detailed analyses and recommendations/warnings extracted from Delphi and focus groups will be covered in sections0 and0. Considering the TF process by itself, the need for experts arises in a few stages – model building and decision making. The reason for involving experts in the model building stage is discussed in the next question. In order to provide the big picture for the decision maker to consider, experts' opinions are included in the TF.

Why do we need experts?

Another basic question to be addressed is the necessity of experts in technology forecasting. Experts are sought for brainstorming for new ideas, faster discovery of emerging technologies and innovation management. Experts are included in the TF activity in technologies where the time lag between TF and technology development is short enough for justification of their inclusion [9].

What are biases that are present in experts' opinion?
Once the experts' opinions are recorded or extracted, there is a fear of whether their opinion is stemmed in some kind of bias. The following reasons are some of the reasons why experts fail in predicting events of global significance, as summarized by Goodwin et al [10]:

i) Tunnel vision: Area of expertise can make the experts think only about their own area and neglect other impinging or even related technologies.
ii) Cognitive bias: Simplification of a complex situation may lead to systematic biases. Some of the heuristics of a cognitive bias are availability, representativeness and anchoring.
iii) Sparsity of reference class: A reference class is an event occurred and the sparsity of the specific type of event in the lifetime of the experts makes the event a less likely event to be predicted.
iv) Lack of extreme events: Events that include extremities are often ignored due to various reasons.
v) Inappropriate statistical models: Models which have abundance of data, but lacking in stating of the underlying assumptions and hence the choice of wrong models can lead to poor prediction of outcomes.
vi) Misplaced causality: Poor inference of causality can lead to incorrect correlations or non-existent correlations.

Some limitations of experts' opinions were added by [11] and [12] are limited understanding of the difference between foresight and forecast, tendency to avoid criticism, intellectual rift between experts.

1.2. Building a Model for Technology Forecasting

The need for building a model will be examined in this section along with the constraint of the model building activity taking finite amount of time. In this light, just like in the previous section of the analysis of the experts' opinions, this section will also follow a similar approach by beginning with the following questions about building models specifically for technology forecasting:

What is a model for technology forecasting?
The ideal properties of an appropriate model required for technology forecasting were summarized as:

i) the models which included consumer and firm homogeneity,
ii) room to include interpersonal communication,
iii) economic factors with numeric values should be includable,
iv) changes in the model with time should be reflected [13],
v) ability to include technology surprises or unexpected events [14],
vi) ability to include tipping point [15].

What are appropriate ways of representing information or model for a forecast?
How do we build a model of the technology to be forecasted?
If the availability of pertinent quantitative information for a particular technology was not considered to be an issue, then building a model by using computer simulations was suggested [14]. There were a number of mathematical modelling techniques used for this purpose – ANN, ARARMA, Single, RBF, (S)ARIMA, univariate time series analysis. One caveat mentioned by Khashei et al [15] was the peril of choosing a single modelling technique as against combining at least two techniques [16], [17], [18, p. 417]. The main risks in choosing a single mathematical modelling technique are: risk of inaccurate forecasts, model may be linear or non-linear and never both. The question of how (a step-by-step procedure) to build a model to represent information will be dependent on the choice of the model(s) and will require expertise in the selected methods. In qualitative modelling, the main focus areas are products and processes. Further discussion on this topic will be covered in the same section.

Why are some models unreliable?

Models are representations of the real world to help to understand the relationships between/among the components of a complex system. Hence, there is a chance that some details or important relationships are not covered by the model or an inappropriate model was chosen for the technology. The choice of inappropriate model may stem from the cognitive bias of the experts, forecaster or the automated program (in case of artificial neural networking or data mining).

Listed below are a few reasons for the unreliability of models to explain a real world scenario (for both qualitative and quantitative models) [11], [19]:

i. Lack of adequate data,
ii. Force fitting data to model,
iii. Difficult to understand, complex models,
iv. Lack of relevant data,
v. Rate of change of technology may be too rapid for the model,
vi. Unprecedented events may affect the effectiveness of the model.

What if there was very little or no reliable data available?

The case where little or no reliable data occurs when either the technology is new or is considered as an emerging technology with a relatively small customer base [4, 16&17]. In these cases, the modus operandi to be adopted is to approach experts, service providers and technology developers to extract information reliably and quickly to build a model for the technology forecasting activity.

What are appropriate classes of representing information or modelling that is useful for a technology forecast?

A comprehensive model for technology forecasting is one that combines both qualitative and quantitative models as well as focuses on products and processes [22]. In this light, several modelling techniques have been reviewed and classified according to their applicability to different situations with a focus on classifying the techniques focused on products and processes. Some of the techniques discussed below have already been discussed in detail in deliverable 2.2 [23]. The modelling techniques are organized according to the following classes:

- Modelling techniques mainly focused on Products,
- Modelling techniques mainly focused on Processes,
- Multi-Purpose Modelling techniques.

That classification of the 29 reviewed product/process modelling techniques is reported in Table 1. Such organization reflects the practical role that these modelling techniques can play within a technological forecasting methodology, as the one to be developed within the FORMAT project.

Table 1 Summary of modelling techniques reviewed along task 2.2. The classification is consistent with what was presented in Deliverable 2.2

Process focused	*Product focused*	*Multi-Purpose*
• EMS • Petri Net • BPMN2.0 • DANE/SBF • EPC • Functional Tree • IDEF0 • IDEF3 • NIST Functional Basis • System Operator	• TRIZ/OTSM-TRIZ Function • SAPPhIRE • Southbeach • TOP TRIZ • TRIZ MTS (Law #1) • Su-Field	• ARIS • DSM • ENV • ERD & eERD • FBS Framework • FMEA/FMECA • FTA • IBIS • Ishikawa Diagram • TRIZ/OTSM-TRIZ Contradiction, • OTSM-TRIZ Network of Problems

Are there other ways of classifying modelling techniques apart from product and process modelling?

For the sake of completeness, the classification proposed in Deliverable 2.2 does not always correspond to the way the different developers proposed their modelling techniques (or consistently with the common practice emerging from the different contributions available in literature). A classification of such a kind is presented in Table 2. Moreover, such reclassification is conveniently divided into four categories, distinguishing the modelling techniques that aim at describing problems from those capable of describing both products and process or just supporting a more repeatable representation of constructs (here called, generically, multi-purpose). This distinction is necessary since problems, in the logic of technological forecasting, have a paramount role in preventing the evolution of technical systems [24].

Table 2 Summary of modelling techniques capable of representing Processes, Products as well as Problems to be solved. The fourth column collects modelling techniques suitable for different purposes

Process focused	*Product focused*	*Problem focused*	*General purpose*
• EMS • Petri Net • BPMN2.0 • EPC • IDEF0 • IDEF3 • NIST Functional Basis	• TRIZ/OTSM-TRIZ Function • SAPPhIRE • Southbeach • TOP TRIZ • TRIZ MTS (Law #1) • Su-Field • DANE/SBF	• FMEA/FMECA • FTA • IBIS • Ishikawa Diagram • TRIZ/OTSM-TRIZ Contradiction, • OTSM-TRIZ Network of Problems	• ARIS • DSM • ENV • ERD & eERD • FBS Framework • Functional Tree • System Operator

How can modelling techniques be evaluated according to their function in technology forecasting?

Since the modelling techniques have several common characteristics as well as differences, a further reorganization in terms of their constructs (i.e., the conceptual information concerning real phenomena), which they are capable of mapping or representing, is provided. For this purpose, the in-depth analysis of the reviewed modelling techniques (Tables Table 1 and Table 2) suggests to classify them according to 5 main clusters, which have been further characterized in sub-clusters as for Figure 1.

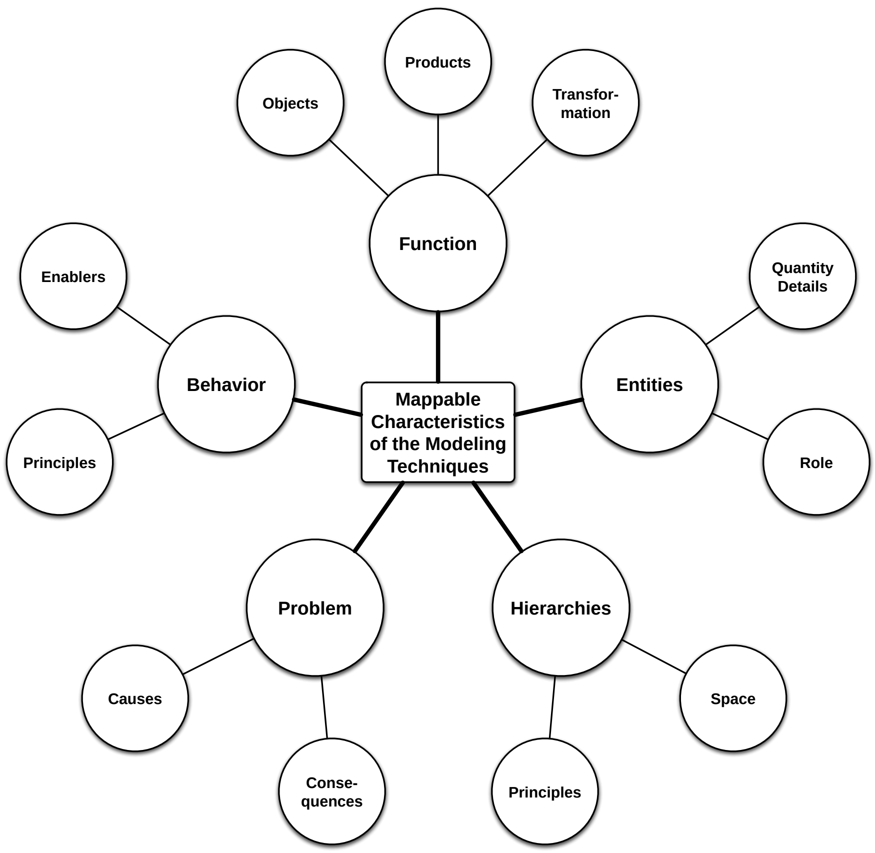

Figure 1 Summary of clusters and sub-clusters for characterizing the different modelling techniques. The sub-clusters aim at providing a general description of what is possible to map with a certain modelling technique

The clusters shown in Figure 1, therefore, allow the identification of strengths and weaknesses for the modelling techniques. In the details, strong and weak points are directly and respectively correlated to the information that a certain modelling technique is able or not to map.
The following bullet list summarizes the meaning of the different clusters:

- Entities/Structures (What composes the system),
    - Quantity Details (Characterization with quantitative details),
    - Role (Characterization of the purpose and/or properties of the entities),
- Functions (What the system is for, i.e. what the system purpose is, regardless the way it practically works),
    - Objects (Characterization of the elements to be transformed),
    - Products (Characterization of the target to be achieved),
    - Transformations (Characterization of the action to be carried out),
- Behaviours (How the system works),
    - Enablers (Characterization of the entities capable of making the system work according to certain principles),
    - Principles (Characterization of the effects, being them physical, chemical,…),
- Hierarchies (Description of Parental relationships),
    - Space (Characterization of inclusion or exclusion relationships),
    - Precedence (Characterization of events or states as sequence of steps in time perspective),
- Problems (What negatively affects the system or prevent its evolution),
    - Causes (Characterization of what triggers a problem),
    - Consequences (Characterization of the effects triggered by causes).

The clusters are to be considered as non-mutually exclusive for the characterization of the different modelling techniques. To this purpose, Table 4 links the classification as for the Deliverable 2.2 with the constructs of the above-mentioned bullet list. The modelling techniques populate the cells of this matrix (with IDs, whose meaning is expressed in Table 3) according to the constructs they are mainly addressing. Besides, whenever a modelling technique aims at modelling more than one main construct (among the 5 hitherto proposed), it is placed in the last column on the right. It collects the modelling techniques mapping a plurality of facets.

Table 3 This table assigns an ID to the different reviewed modelling techniques as for Deliverable 2.2. It serves as a legend for better understanding the content of the Table 4, Table 5 and Table 6

#Ref	Name	#Ref	Name	#Ref	Name
1	ENV	11	ER diagram	21	FBS
2	EMS	12	IDEF0	22	IDEF3
3	SAPPhIRE	13	DANE/SBF	23	Petri Net
4	IBIS	14	Ishikawa	24	FTA
5	NIST Functional Basis	15	Minimal Technical System	25	Design Structure Matrix
6	TRIZ Function	16	TOP TRIZ	26	Su-Field
7	OTSM-TRIZ Contradiction	17	OTSM-TRIZ Function	27	Network of Problems
8	Functional tree	18	System Operator	28	Extended ER diagram
9	Southbeach	19	EPC	29	FMEA/FMECA
10	BPMN 2.0	20	ARIS		

Table 4 The double-entry table presents in the first column the classification as for Deliverable 2.2. The first row organizes the different constructs hereby introduced for the strength, weakness and integrability analysis

	Main Focus on Entities	Main Focus on Functions	Main Focus on Behaviors	Main Focus on Hierarchies	Main Focus on Problems	Plurality of Facets
Focus on Products		16	3, 6, 15, 17, 26			9
Focus on Processes		2, 12	13, 22, 23	8, 18		10, 19
Supporting & Multi-Purpose	1, 11, 28	5	25		4, 7, 14, 24, 27, 29	20, 21

The description of the clusters, provided above, as for Figure 1, derived in part from the logic of the FBS framework by Gero and Kannengiesser [25]. It clearly shows that some concepts can also have some overlapping with other ones in the list. For instance, the role of entities is strongly linked with their purpose in the technical system, namely their functions. Moreover, such a role also affects the overall way the technical system works, namely its behaviour. To this purpose, a more detailed analysis of the modelling techniques is presented in the double-entry Table 5 and Table 6 (rows for techniques and columns for constructs), since they can map more than a specific construct at a time, even beyond the overall logic for which they have been developed.
To this purpose, so as to facilitate the development of an original modelling approach to be integrated within the FORMAT forecasting methodology, these tables present a classification of the different techniques with a scale based on three colours, having the following meaning:

- Green - the technique is capable of mapping (at least partially) the specific construct,
- Yellow - the technique can be integrated with other features so as to map the specific construct,
- Red - the technique presents several problems, even if integrated with other features, to map the specific construct (or of integration of new constructs).

Please, also note that squares, circles and exclamation marks have been used just for the purpose of automatically formatting the Tables with appropriate colours, so as to ease their reading. Moreover, the assessment of Tables Table 5 and Table 6 should be conveniently considered as a judgment concerning the adoption of modeling techniques for the purposes of the FORMAT project. In other words, the criticalities emerged in those tables are not necessarily reflecting limits, which could prevent their application for other purposes.

Table 5 Details about the capability of the different modelling techniques to represent the considered constructs - Part 1

		Behavior		Entities		Function			Hierarachy		Problem	
ID	Modeling techniques	Enablers	Principles	Quantitative details	Role	Objects	Products	Transformation	Precedence	Space	Causes	Consequences
1	ENV model	x	x	x	o	x	x	!	!	x	x	x
2	EMS	o	o	o	!	x	x	x	o	!	!	!
3	SAPPhIRE	x	x	o	o	x	x	x	x	o	!	!
4	Design VUE - IBIS (Issue Based Information Systems)	!	!	!	!	!	!	!	x	o	!	x
5	NIST Functional Modeling	x	x	o	o	x	x	x	!	!	!	!
6	TRIZ Functional Modeling	o	x	o	x	o	o	x	x	o	x	x
7	OTSM-TRIZ Contradiction Model	!	o	x	o	!	!	!	!	!	x	x
8	Function Tree	!	x	!	!	!	!	x	x	!	x	x
9	Southbeach Notation	o	x	o	x	x	x	x	x	o	x	x
10	Business Process Model and Notation (BPMN)	x	x	x	o	x	x	x	x	x	!	!
11	Entity-Relationship Diagram	x	x	x	o	x	x	x	!	o	o	o
12	IDEF0	x	x	o	x	x	x	x	x	x	o	o
13	DANE/SBF	x	x	x	x	x	x	x	x	o	!	!
14	Ishikawa	!	o	o	o	!	!	o	x	o	x	x

Table 6 Details about the capability of the different modelling techniques to represent the considered constructs - Part 2

		Behavior		Entities		Function			Hierarachy		Problem	
ID	Modeling techniques	Enablers	Principles	Quantitative details	Role	Objects	Products	Transformation	Precedence	Space	Causes	Consequences
15	Minimal technical System	!	!	!	o	o	o	o	o	o	!	!
16	Tool-Object-Product	o	o	o	x	x	x	x	o	!	x	x
17	OTSM-TRIZ Functional Modeling	o	x	x	x	o	o	x	x	o	x	x
18	System Operator	!	!	o	!	o	o	x	x	x	x	x
19	Event Driven Process Chain (EPC)	x	x	o	x	x	x	x	x	!	o	o
20	Architecture of Integrated Information Systems (ARIS)	x	x	x	x	x	x	x	x	x	!	!
21	FBS	!	x	x	o	x	x	x	x	x	o	o
22	IDEF3	x	x	o	x	x	x	x	x	o	o	o
23	High Level Petri Net Graph	!	x	x	!	x	x	x	x	!	!	!
24	FTA	!	x	o	x	o	o	x	x	o	x	x
25	DSM (process)	o	x	x	x	o	o	x	x	o	o	o
25	DSM (product)	x	x	o	x	o	o	x	!	!	o	o
26	Su-Field Model	x	x	o	x	x	o	x	o	!	x	x
27	Network of Problems	o	o	!	!	o	o	o	x	o	x	x
28	Extended Entity-Relationship Diagram	x	x	x	x	x	x	x	!	x	o	o
29	FMEA/FMECA	!	x	x	x	o	o	x	x	x	x	x

More into the details of the different modeling techniques, the main criticalities (red cells) for the adoption within a technology forecasting modeling approach, as emerged in Tables Table 5 and Table 6, are discussed in the following paragraphs.

For what concerns the description of Functions, some of these modeling techniques are currently not capable of providing a repeatable representation of both the object and the product of a function (please see EMS model in [23] for the meaning of *object* and *product* in this context). The IBIS notation aims at mapping the design rationale, thus mostly addressing decisions to face design problems. In the same perspective, even if with very different features, both the OTSM-TRIZ Contradiction Model and the Ishikawa Diagram are not capable of easily representing the purpose of a technical system. In other words, since they aim at characterizing problems, they map undesired functions and, therefore, the transformation from object to product can be hardly implemented in those representations.
On the other hand, both the Functional Tree and the ENV model cannot properly characterize the function, intended as the motivation behind the existence of a certain technical system. The former can properly map actions, rather than transformation from objects to products. The latter, in turn, can characterize entities but it is not capable of describing actions, nor transformations.

The description of a system behaviour can be considered from a wide variety of perspectives and almost all the different modelling techniques describe, at least, some facets concerning the way a certain system is working or a process is structured. Nevertheless, some of these techniques, according to the purpose they have been developed for, are less suitable for being integrated with others in a meta-model to be used within a forecasting methodology. For instance, all the modelling techniques aimed at addressing the representation of problems (e.g., IBIS, OTSM-TRIZ contradiction, FTA, FMEA/FMECA, …) just take into account a small part of the behaviour, mainly concerning the emergence of side effects, thus overlooking how the system delivers its main useful function or the combination of stages a process consists of. More specifically, the principles characterizing a certain behaviour can be more easily mapped in terms of cause and effect relationship. However, most of the reviewed modelling techniques are still missing specific constructs to display the properties characterizing the way a certain technical system is functioning.
On the other hand, the High Level Petri Net Graph (HLPNG) as well as the System Operator or the Functional Tree are capable of pointing out the sequence of stages occurring along a process or characterizing the way a system is working. Nevertheless, these models are not directly clarifying which are the properties or the entities allowing the systems or processes to behave according to a working principle. Moreover, the System Operator does not have a specific construct to point out the principles involved in the way the system (or process) produces their expected outcome. The FBS framework, when used as a way to represent alternative technologies instead of describing cognitive processes, can allow designers to classify the technical solutions according to their working principles. Yet, there is a substantial lack in connecting these principles with the properties that are not necessarily representable as different structures (for instance, as a set of entities).

As for the capability to represent Behaviors, the Functional Tree cannot integrate (except with radical changes) both the role of entities and their quantitative details. The same limitation characterizes the IBIS notation, since there does not exist a specific construct capable of distinguishing or characterizing entities in the flow of design choice and assumptions that such a model can map.
Energy-Material Signal modelling, System Operator and High Level Petri Net Graph are all capable of collecting and representing entities. Nevertheless, these three modelling technique require significant changes and introduction of new features for mapping the specific role that the different entities play along a process or inside a product. In details, the EMS model can just map entities as the flows to be modified by a technical system, thus neglecting what is concretely changing those flows. The System Operator, in turn, can just collect entities at different detail levels, so as to highlight their parental relationships and not their role in the delivery of a certain function. Moreover, HLPNG shows the changes of state that occur in entities. Yet, the mathematical approach, which characterizes the specific behavior along each state, does not meet the need to provide a modelling technique that is easy to be learnt and used. Unlike the HLPNG, the Network of Problems and the Minimal technical System Model can integrate knowledge elements representing the role of different entities, respectively as textual description and according to the logic of Engine, Transmission, Tool and Control elements. Notwithstanding, they cannot easily integrate quantitative information for the characterization of the technology to be modelled.

The NIST functional basis, in the context of describing the parental relationship in both time (precedence) and space, can be just used as a way to support other modelling technique in describing functions and entities with improved repeatability. In other words, it is not easy to implement within this logic space and time descriptions between functions and entities, unless this technique gets used in combination with other modelling techniques (e.g., EMS). The same limitations in representing both space and time hierarchies characterize also the OTSM-TRIZ Contradiction Model and the Design Structure Matrix (DSM) for product modelling. In the first case, the model just describes the elements involved in the problematic situation in a specific time frame (instant), without considering the parental relationships among entities. In the second case, the DSM for products just allows to map the functional relationship between elements, thus neglecting the "inclusion relationship" as well as the time sequence with which such functions occur during the functioning of the technical system.
The ontologies for describing entities, such as ENV, ERD and eERD allow, at different extent and in the first case with some modifications to be introduced, the representation of parental relationship. On the contrary the

time perspective is completely absent, as the representation of entities is static and overlooks the potential changes they undergo. In addition, different modelling techniques as EMS, TOP TRIZ, Su-Field Models, EPC and HLPNG are characterized by an event- or state-based logic that makes possible to describe the sequence of actions in time. Nevertheless, all these techniques do not allow the description of parental relationships in space, unless they would be enriched by appropriate and dedicated constructs. The same lack characterizes also the Functional Tree modelling technique that, contrarily to the abovementioned ones, allows a time-dependent description of functions and sub-functions according to a tree pointing out just the necessary conditions for a function to appear.

Lastly, the capability to represent problems as causes and consequences (or effects) is a distinctive feature of the modelling techniques presented in the third column of Table 2. Some other techniques can be quite easily integrated with new constructs for describing undesired effects, as well as their causes, occurring with a product or during a manufacturing process. Such integration, on the contrary, may require substantial or radical changes for some other techniques. For instance, both the EMS model and NIST Functional Basis, given their current framework, can hardly represent problems emerging within a technical system (being it a product or a process). Indeed, the black box logic used for representing functions can just show the effects on the outgoing flows, thus overlooking the causes determining them. Moreover, these modelling techniques do not describe the potential problems that may also emerge within the technical system (e.g., the system damaging itself) in both the terms of causes and effects. Analogous considerations are valid for the HLPNG.
Similarly some other techniques as SAPPhIRE, DANE/SBF and MTS are just capable of representing the conditions and the states for achieving a functional outcome (the first two techniques) and the elements that transfer energy from an "Engine" to a "Tool" with the purpose of achieving a desired transformation for the object of a function. In other terms, their logic aims at representing only the desired transformation, implicitly neglecting the different situations (for instance, due to external perturbations) that may trigger an undesired effect reducing the capability of the systems to carry out its function.
Analogous considerations can be done for more complex modelling techniques, such as BPMN2.0 and ARIS. In these cases, the representation of causes and consequences of problems is probably less challenging because of the presence of constructs, such as the logical gates AND, OR and similar ones. However, a consistent modification in terms of representation should be introduced to highlight the differences between desired and undesired situations, especially for specifying the necessary conditions (not just the causes) concurring in the emergence of such problems.
Differently from all the above-mentioned techniques, the IBIS notation can clearly represent problems, despite a plain distinction between causes and effects is not so well addressed by its characteristic constructs. Usually a problem (issue) is described as an undesired effect to be tackled by some solution concepts (answers). In case a new problem is connected to an answer, such answer is a likely cause for triggering the new issue. Moreover, a problem can trigger a set of different (sub)problems. The initial problem is considered as the primary cause. Indeed, this technique mainly aims at representing design rationale and this implies that substantial modifications should be introduced for distinguishing hypothetical solutions from real ones, as well as parental relationships between problems (nor in time or space, but as logical consequences) so as to really map the causal relationships behind the emergence of undesired situations.

According to the hereby-presented analysis, it follows that some models are capable of representing almost all the different constructs, e.g. BPMN2.0. Nevertheless, it is worth mentioning that all these different modelling techniques miss to represent the existing links between products and process. Even ARIS (which has the capability to represent processes and products as, respectively, a sequence of events through the Event-driven Process Chain and the extended Entity-Relationship Diagram) just map the presence of product-related entities along the process. More specifically, it practically misses the rationale behind the need of certain process stages (or technologies) as the way to progressively confer new properties to the raw materials till they become a fully finished product.

To this purpose, the development of a new modelling technique to be implemented into the technological forecasting methodology, which is capable of overcoming the inadequacies of the existing ones in addressing both product and process characteristics and links, is strongly beneficial.

How are mathematical models classified according to the need of technology forecasting? How can mathematical models be evaluated on the basis of the need in forecasting activity? How is reliable data extracted? Why does modelling take time?

These are questions that need further attention and time devoted and has been highlighted as work to be done in the future in Section 4. These questions have been included here to indicate the importance of such questions in the context of the motivation of the report.

1.3. Manufacturing Technologies Context

Scott [26] identified 10 key issues in manufacturing technologies and one of the key problems identified was "strategic planning for technology roadmapping". Baines et al [27] examined strategic firm acquisition in light of selecting the correct manufacturing technology keeping in mind that a wrong selection of technology means wrong investment. Problem solving, managing structure of knowledge and performance were considered as the drivers to adapt to discontinuous change in the manufacturing sector. Walsh [28], however, segregated types of technologies based on the level of disruption and suggested different strategies for sustaining and disruptive technologies. A similar argument specifically for nascent industries or emerging technologies was given in section0. Walsh [28], also added that appearance and evolution of disruptive technologies had minimal or absence of contribution from existing manufacturing infrastructure, thus making the task of forecasting harder for disruptive technologies. Learning curves (cost per unit and experience acquired were used as parameters) have been used in aerospace and semiconductor manufacturing as a way to plan for man power and resource consumption, once a technology was self sustaining [29]. One example of the learning curves approach was published by Cañizo et al [30]. A technology foresight for the field of photovoltaic technology was achieved by dividing cost per unit into individual manufacturing costs of each manufacturing process in a photovoltaic cell. Gindy et al [31] analyzed the semiconductor based manufacturing technologies and highlighted the major features required for technology roadmapping in manufacturing technology as:

a) Identification of gaps,
b) Prioritization of problem areas,
c) Goal setting or planning action steps,
d) Transmission of information across the entire organization.

These features form the set of criteria to oversee the ease of use of some of the tools entirely in the context of manufacturing technology as will be discussed in subsequent sections. Gindy et al [31] had also enlisted some unsolved or partially solved challenges for tools of roadmapping, namely:

a) Development of quantitative and qualitative data collection strategies,
b) Problem area prioritization,
c) Inclusion of both financial and non financial factors for evaluation of technologies,
d) Communication strategies for expression of the plan across the entire organization,
e) Expert handling and enabling transfer of information between them as well as consensus building.

With the above set of challenges, the TF tools were evaluated for their strength in achieving these targets, with the implicit assumption that these set of challenges were for self sustaining or mature manufacturing technologies. A different set of challenges is more likely to emerge for nascent industries and a thorough study is recommended.

2. Analysis of Widely Cited TF tools and Recommendations/Warnings Extraction for Manufacturing Technologies

Slupinski [1] had tabulated TF methods based on their popularity in Google Scholar. The top 3 TF tools in each of the four above-mentioned categories were chosen for recommendations or warnings extraction for the development of the new FORMAT technology forecasting methodology (see Table 7). The rationale behind choosing TF tools based on number of results from Google Scholar is the ready availability of information of experiences with these tools. The assumption was that more the number of publications available in Google Scholar, the widely studied the TF tool would be. Based on the experience collecting literature from these TF tools, the researchers have added 2 more tools – relevance trees and imitation and diffusion coefficients.

Table 7 shows the categories of TF techniques with the 3 most popular techniques, based on Google Scholar searches. The values in brackets indicates the number of publications

Causal Model	Phenomenological	Intuitive	Monitoring & Mapping
Artificial Neural Networking (40000)	Forecasting by analogy (14000)	Delphi (25900)	Environmental monitoring (23200)
Multi criteria analysis (11200)	Simple regression (10300)	Focus groups (18400)	Stages of development (correlation) (16000)
Systems perspective (6920)	Statistic modelling (10100)	Science fiction (14200)	SWOT forecasting (12700)

The categorization of TF tools into 4 major categories was proposed by Dmitry Kucharavy (in his working material) and was cited in the report by Slupinski [1] and has been used in this report as well. The 4 major categories of TF tools are causal, phenomenological, intuitive and monitoring & mapping. The TF tools have been analyzed for their generic applications and excerpts of the strengths and weaknesses for each of the tools in the next sections.

2.1 Causal Models

Causal models are those TF techniques where the basic relationship between variables and outcomes is fairly well understood or at least the relationships are acknowledged to exist.

Multi criteria analysis

FOR LEARN project [32] describes this method, which aims at comparing various solutions or paths forward in a technology to a list of criteria, while using weighted averages to evaluate the actions or solutions available. The method is used as a decision making tool in the strategy phase of a project. Particular attention has to be paid to the criteria chosen as was done for the evaluation of alternatives to mobile phones in Işıklar et al [33].

Strengths

This method is largely a survey-based method and allows for changes even after the initial survey is done. The initial forecasts can be course corrected after new data or trends start emerging. Since the choices and weightages are numeric, the decisions and the justification for decisions is straight forward.

Weaknesses

Dependencies, synergies between the listed actions may complicate the model. This method is meant for simple models.

Artificial Neural Networking

Artificial Neural Networks (ANN) derive their inspiration from neural networks in nature [34]. The forecasting usually involves a phase of training where the network is subjected to a sample of data and then extrapolated to the unseen part, which may pertain to the future. When the variables are known a priori, the approach is called parametric and where the network starts with only data, the approach is called non-parametric [17]. ANN can be used in areas such as finance, business, electric load forecasting and airline passenger traffic.

Strengths

The ANN system learns from input data and even though the individual nodes may be inefficient and slow, the overall system is quick and efficient in delivering forecasts. The networks work very well when the time series data is non-linear, dynamic, complex and the inter relationship between the variables is unknown or unclear.

Weaknesses

Integration into system level long-term prediction needs to be done [35]. This method needs the users to have experience and time to get reliable results and may be complicated for simple systems where there is considerable understanding of the dependent parameters.

Systems Perspective

This method largely focuses on considering the “bigger picture” of the system, or the system as a whole, the parts of the system and the relationship between them [36]. In addition to the system, the neighbouring “universe” where the systems exert influence needs to be identified. The ability to understand complexity and the need to be multidisciplinary are critical to this method [37]. The method has application in varied fields, as for instance video games, psychology and hospital systems. There is no system that the method is particularly suited for.

Strengths

Rapid change, “wicked problem”, high complexity problems can be handled well.

Weaknesses

Slow start, slow process and slow decision making are part and parcel of the systems perspective. Ability to think about the system level does not lead to action and hence action has to be separated from system thinking.

Relevance Tree

A technique that forecasts several possible futures in a graphical format and also has a probability associated with each path of technology. In some cases, there may be a weightage or relevance associated with the possibility. The tree structure is in the form of a hierarchy of all the possibilities.

Strengths

System wide perspective rich with details about the system is available at a glance.

Weaknesses

The technique may need a human to interpret the results and, hence, the interpretations may be subjective [38].

2.2 Phenomenological Models

Phenomenological models are usually concerned with the technology as a single piece rather than focus on the components or structures that go into making the technology.

Forecasting by Analogy

“This project is as big as the Manhattan Project” is one of the analogies that can be used to convey what the method is all about. The scale or time period of an event in the past can be projected onto the situation at hand [39]. A case-based forecasting system (CBFS) was developed by automating the process of identifying similar cases from history to generate forecasts about the future [40]. The CBFS method was used in project management to generate similar projects that have been executed successfully in the past.

Strengths

Current and historic examples can be compared in a systematic way and this approach can be extended to new products as well.

Weakness

People are unpredictable and similar situation in the past does not imply similar results

Simple Regression & Statistic Modelling

Simple regression, statistic modelling and data mining are all clubbed under one subheading because of similarities in the methods [41–43]. In these mathematical methods, the main assumption is that the data needed for the forecast is available [44]. The data is used to build models that can be used to extrapolate and generate predictions. The applications for these methods are numerous and apply mainly to areas where there is extensive data and where the application of mathematical recipes yields results. Some example applications are genetics and computational fluid dynamics.

Strengths

Empirical models based purely on data mining or historic data can include variables that the expert overlooked.

Weaknesses

The data based models do not explain the underlying truth of why the technology is progressing in a particular direction.

Imitation and Diffusion coefficients

Once the technology is in the initial stages and the growth is slow, firms monitoring the technology tend to imitate the technology from competing firms. This imitation depends on the profitability of the technology and the initial investment [45]. Once the technology reaches a slowdown phase, technology substitution takes over when consumers choose a competing technology to maximize the utility of their finite resources. This consumer choice and price points were considered to be pivotal in estimating the rate of technology substitution [46].

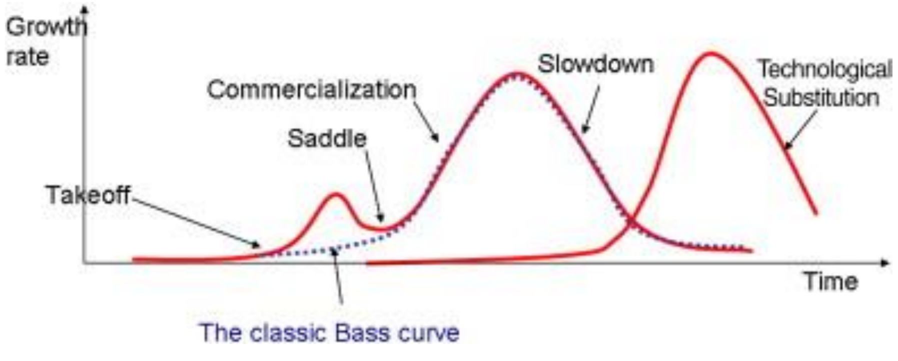

Figure 2 Technology adoption or diffusion consists of several phases, which include customer driven parameters and technological limits [21]

Strengths

Peres et al [21] suggested that technology adoption model is not a smooth Bass curve, but consists of saddles, take off or inflection points and turning points, as illustrated in Figure 2. The models where the imitation and growth coefficients were changing with time, the models seemed to fit better for adoption of technology across technology generations [47].

Weakness

As with any other mathematical modelling technique, the reason why technology diffusion does occur in a particular direction is unknown and needs human intervention.

2.3 Intuitive Models

Intuitive models are primarily based on instincts or gut feelings and may not always be substantiated with hard evidence.

Delphi & Focus groups

One of the most popular methods for knowledge extraction from experts and other important stakeholders has been the Delphi method. This method involves questioning a panel of experts and eliciting forecasts on specific technology with minimal face-to-face interactions. A moderator collates the data and conducts multiple rounds of interviews where the panellists are allowed to withdraw, change or justify their predictions. At the end of the rounds a report is generated with all the noted predictions, objections and changes [6–8], [48]. Delphi started out as a forecasting method, but has many variations now in fields as management, planning, and education apart from forecasting.

Strengths

Incorporates all the advantages of a committee ("2 heads are better than one" and taking into account a number of factors that affect the forecast) and allows for correcting forecasts without the need for a consensus. There is no room for arguments and, hence, the forecasting sessions are focused on technology forecasting.

Weaknesses

There is room for introducing a bias by way of the questions from the moderator. If all the experts involved are misinformed, then the forecasts also tend to be erroneous and correction is difficult. Collating data from experts and preparing for the different rounds of Delphi is time consuming and expensive. Getting the experts' time can be expensive as well.

Science Fiction

Science fiction is popular and is often used to look at what might potentially happen in the future with warnings about technological oppression and future directions [49], [50]. The technique involves looking for major leaps in technology in works of science fiction. Application areas include nanotechnology, medicine, computers [51–53].

Strengths

Science fiction shapes the science of the future and the trends of technology influence science fiction. As a technique of forecasting, this tool is easy to understand.

Weaknesses

The forecasts may be vague and cannot be used for policy changes or planning.

2.4 Monitoring and Mapping

This set of techniques largely consists in following a technology through the passage of time and may include scanning through published literature and mapping existing sources of information.

Stages of development (correlation)

The Stages of development technique is very similar to environmental scanning in terms of tracking early information, however the technique differs in the source of information. The information is taken usually from an early stage of development of an innovation [54]. The example used is that of a feature of a car, which moves from experimental to the luxury segment and then to the mass market. Thus detecting this lead-lag correlation, one can predict the features for future cars in the mass-market segment. Examples of application of this method has been cited in nanotechnology and human interface devices [55].

Strengths

Several features of a technology follow specific patterns in the stages of development and therefore can be a useful indicator of an upcoming technological feature.

Weaknesses

The forecaster should be well aware of the technology and the positive trends to latch onto and beware of false trends.

Environmental Monitoring

The method of scanning a technology for early indicators of a breakthrough is called environment monitoring [56]. The method is described to be very rigorous and involves collection, screening, evaluating and setting a threshold for a particular technology. The method involves full-time dedicated personnel identifying information in the above-mentioned stages of environmental monitoring. Some of the sources of data for monitoring are: a) information collection services, such as Google Scholar or Google Alerts, b) essays by experts, c) literature review, d) key person and conference tracking. Environmental monitoring or scanning has been used in areas as strategic planning for corporations and education planning [57–59].

Strengths

Technology “Breakthroughs” bring about the most change and usually precursors or significant events. The detection of these precursors or events can lead to the correct prediction of “breakthroughs”.

Weaknesses

Requires dedicated personnel monitoring technological factors rigorously.

Strengths-Weaknesses-Opportunities-Threats (SWOT) forecasting

SWOT analysis is primarily used to analyze the current situation of a technology, but the opportunities and threats can be used to assess the future of a technology [60]. Application of this method has been in various fields, such as energy, telescopic drilling [61], [62].

Strengths

Non-technical nature of the tool increases ease of use along with being highly flexible.

Weaknesses

Lack of prioritization and possible vagueness in the usage of words.

Scenario Planning

This tool is a story-telling tool that can be used to convey complex situations and systems to a broad audience. The method consists of 4 stages: i) Framework, ii) Forecast technology, iii) Plot scenarios and iv) Write scenarios [63]. The technique has been extensively applied in information and communications technology (ICT), change management studies, government policies, to name a few [64].

Strengths

A decision-making tool since complex systems can be explained to the stakeholders. Flexibility of the tool allows for changes to be made quickly after the decisions have been taken.

Weaknesses

Uninformed users can interpret the results as the “only future” and can be biased as result. Alternatives predicted by the scenarios that may be considered as unpopular with the decision makers may be deleted to avoid debate or a non-consensual state [65].

2.5 Recommendations and Warnings Extracted for Manufacturing Technologies

The best TF tools are those that can satisfy all the criteria, which are critical for TF tools used in manufacturing technologies, as mentioned in section 1.3. As analyzed in Table 8, there are a few recommendations and warnings that can be extracted from the various tools for each of the criteria listed. All the tools mentioned in the preceding sections were analyzed against the criteria critical for roadmapping for manufacturing technologies one by one and the results are reported textually in Table 8 and pictorially in Table 9.

Table 8 The list of extracted recommendations and warnings from the widely cited TF tools in the context of manufacturing technologies

Criteria	Recommendation(R)/Warning(W)		Source
Experts handling	R	*“Two heads are better than one”* This statement embodies the power of a committee. There have been studies [66] to show that the number of factors extracted from a committee was more than that individually extracted from committee members.	Delphi
	R	*Experts should be assured that there will be no misinterpretation of their forecasts* Forecasts are snippets of the future in the form of a probability or a definite situation in the future, so there will be room for misinterpretation. Hence, there is a need for unambiguous communication of the situations, as described by the experts or forecasters.	Scenario planning
	R	*The simplicity of weighted aggregate criteria can aid in decision making* The ultimate aim of FORMAT project is to aid the decision maker in interpreting and taking informed decisions about the future of technology and associated actions. The main recommendation from multicriteria analysis is that the decision made is complemented with a simple number or rubric, which helps to justify such a decision.	Multicriteria analysis
	W	*An error made by the entire panel may remain undetected* In iterative, anonymous group discussions, several errors do get corrected, but there is a finite possibility that an error, which is unknown to all the members in the panel, may remain uncorrected.	Delphi
	W	*Slow decision making* The perspective gained from systems thinking is a big picture scenario and may contain details from not only the system of interest, but also from systems around and subsystems contained in the system. This information overload may hamper or slow down decision making.	Systems perspective

	R	*Detection of precursors to breakthroughs or upcoming technological feature can aid in forecasting breakthroughs or features* Breakthroughs or disruptive innovation is usually preceded by precursors, thus the premise is that detecting the precursors can be useful in predicting the disruption in current technology. An example of such a precursor is - features introduced in luxury segment of a product are later introduced into a mass segment with a time lag.	Environment monitoring, Stages of Development
Quantitative/ Qualitative model data extraction	R	*Technology mining or neural networks can generate parameters and do "sense making" obviating the need for experts* As discussed in section 1.2, ANN and other data-mining recipes can generate models based on available and reliable data and generate more factors relevant for model building than by conventional committee-based knowledge extraction [67].	ANN, data mining
	R	*In the evolution of technology, data can be extracted for models to be corrected* After the introduction of a technology, there will be a need to update models, as there will be imitation of accepted early stage technologies. This correction can be included in the original model.	Imitation coefficients
	W	*Biases may be introduced by the moderator* The moderator or forecaster is usually the mediator between the quantitative/qualitative models and the experts in many cases and is usually knowledgeable about the field of technology. This prior knowledge of technology may unintentionally hinder the impartial extraction of knowledge.	Delphi
Communication Strategy	R	*Scenarios of the future described to non-experts unambiguously* The decisions made and the forecasts predicted need to be communicated across an entire organization or all the stakeholders. Hence, the scenarios depicted should leave no room for different interpretations other than the intended interpretation.	Scenario planning
	W	*Non-experts may think the predicted future is the only future* The peril of the clear portrayal of a forecast is that the recipients of the scenarios may consider them as the definite future.	Scenario planning
	R	*Provide clear and rich imagery of the future along with scenarios as long as they are useful for decision making or making policy changes* Stories and artists' depiction of the future not only help in communicating the future, but also in inspiring technologists to aspire for the depicted future (normative)	Science Fiction
	R	*Non technical nature of the tool increases ease of use along with being highly flexible* The overall objective of the FORMAT project is to make the technology forecasting a reproducible and repeatable exercise, without the need for a methodological expert. This	SWOT Forecasting

		recommendation is to make the TF method as easy as possible and also for any purpose deemed relevant by the user.	
	R	*System wide perspective rich with details about the system is available at a glance.* A network of possibilities drawn up along with numeric probabilities of occurrence of the potential scenarios should give a snapshot of the system. The probabilities are estimated on the basis of subjective judgments made by a panel.	Relevance Tree
Problem area prioritization	R	*Forecasting sessions are focused on technology forecasting* When face-to-face committees meet, there is a tendency to focus on arguments, consensus building and power play, while the preferred state is to be focused only on technology forecasting during these sessions. If the focus remains on the activity of delivering technology forecasting predictions, the results are far better than the ones, which tend to be consensus driven.	Delphi
	R	*The methodology has to be flexible enough to accommodate changes after initial trends emerge and decisions taken* Initial forecasts are based on various assumptions, which might be tested during the adoption phase. If the assumptions turn out to be wrong or there are new data points that need to be included, the methodology should be flexible to accommodate.	Multicriteria analysis
	R	*Rapid change and "wicked" problems should be handled well* Complexity, variety, rapid changes in time should be handled by examining the system at a "big picture" level. The system, the relationships of the components and the interactions with the surrounding systems should give a better handle on complex systems than the reductionist approach of understanding the system.	Systems perspective
	R	*There should be dedicated personnel available for tracking technology and should acquire adequate knowledge of problems in areas of technology* When there are dedicated personnel tracking a particular technology, there can be insights from them on the intricacies of the future of the technology. These personnel become adept at probing the experts for appropriate information. With this experience, the personnel highlight problem areas of extreme importance to the teams solving these problems. One example of these dedicated personnel is the role of intellectual property (IP) analyst. IP Analysts are well aware of the technology field and can give a prioritized list of problems (or white spaces) to be solved.	Environment monitoring
	R	*Examples from the past highlight patterns of occurrence of problems* Documenting problems in technology is imperative since the analysis of these problems will give insights into the frequency of occurrence of similar problems. For example, a software testing team documents the set of frequently recurring bugs in	Forecasting by Analogy

		a software and the approach that was taken to solve them. The subsequent projects can anticipate the potential bugs and prioritize them based on documentation available.	
	W	*A forecast lacking prioritization and consisting of vague usage of words* Presentation of problems as a list without priorities is to be avoided. Additionally, words are to be chosen carefully as the same set of words could imply a different interpretation.	SWOT forecasting
	R	*There should be probabilities or numbers associated with every possible future path* For every component or every group of components considered in the system, there exist potentially a number of future paths ahead. Probabilities associated with each of these paths are assigned by a panel and represented visually to be available as a snapshot. Once a matrix of all possible paths is listed down, feasibility evaluation of the various combinations of these paths takes place. The best course of action will be decided based on available resources.	Relevance Tree
Financial and non-financial factor inclusion	R	*Exhaustive inclusion of all relevant factors that is known to committees that affect the forecast* All relevant factors, irrespective of whether they are financial or non-financial, must be listed. The relevancy of factors is a matter of subjective judgement at this stage. Iteration is recommended to ensure exhaustivity.	Delphi
	R	*Survey based weightages are assigned to measurable and immeasurable factors* Weightages assigned to factors are based on their importance in the technology under evaluation. Once assigned (by a panel of experts), the aggregate of the weightages based on the subsequent survey can be used to aid decision making.	Multicriteria analysis
	R	*Models can accommodate both measurable and immeasurable factors* A combination of qualitative and quantitative models which include measurable and immeasurable factors explain reality much better than the ones which have only one of them [68].	ANN, data mining

3. Discussion

The motivation of this study was not only aimed at examining recommendations and warnings from established TF methods but also to contribute to the development of a robust TF methodology imbibing the strengths of the methods studied. Hence, based on this motivation, the study of literature revealed 4 key stages in the making of a TF:

1. People: People are essential and key to the success of a TF [69],
2. Models: Mathematical or analytical models are deemed necessary for accurate and precise predictions of the future [70],
3. Course correction is imminent in some cases where the forecasts need to be revisited and corrected for accuracy and for change in external conditions [71], and
4. Impact analysis and feedback: The consequence of action based on the technology forecasts need to be factored in.

Table 9 Matrix showing qualitative assessment of TF tools against set of criteria that manufacturing roadmapping tools need [31] (▲ represents the strength of a tool, ▼ represents the weakness, a blank is where the tool is inadequate, ▲▼ refers to a contradiction, where the tool is strong and weak within the same criteria)

	Delphi & Focus groups	Multi criteria analysis	Stages of dev	ANN	Simple regression & data mining	Systems Perspective	Science fiction	Imitation coefficient	Env monitoring	Forecasting by analogy	SWOT	Scenario planning	Relevance Tree
Quantitative & Qualitative data collection	▲▼			▲	▲			▲					
Prioritization of problem areas	▲	▲				▲	▼		▲	▲	▼	▲	▲
Fin and non-financial factor evaluation	▲	▲	▲	▲	▲				▲			▲	
Communication strategy							▲				▲	▲▼	▲
Handling of experts	▲					▼			▲			▲	

These 4 stages have an iterative loop where the progress moves from stage to stage and sometimes back into some other stage. For example, the results or forecasts from People stage need to be validated by a model and during the course of time needs to be corrected in the course correction stage. After the course correction, the model may still need minor changes, thus leading to the model stage again. Figure 3 shows the interaction between the stages of the model. This is not a linear model and should allow for back and forth movement of flow of steps across stages. For example, the experts (People stage) have to be approached every time there is a change in conditions either through active plans (Impact stage) or while watching technology (Course correction stage).

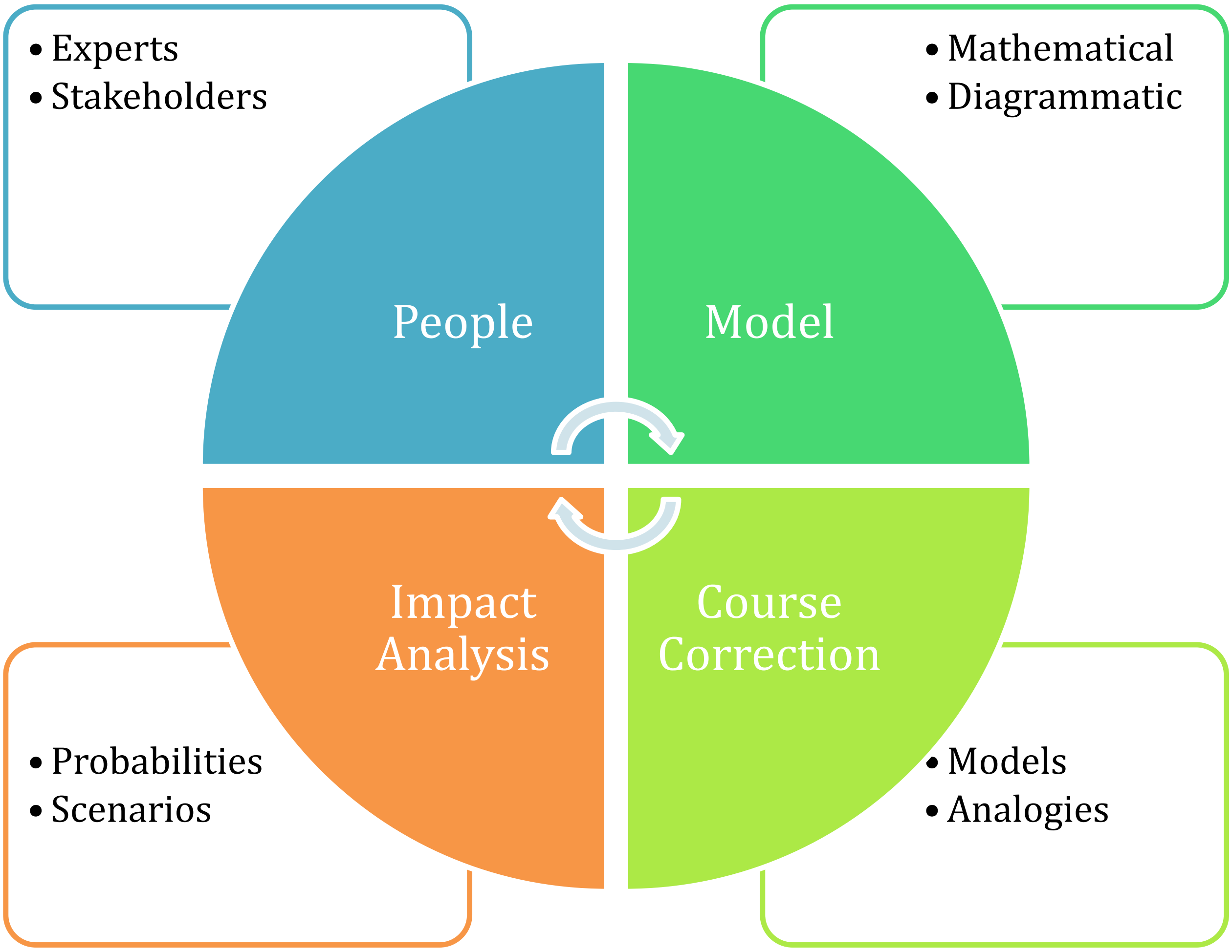

Figure 3 The 4 stage model for TF consisting of people, models, correction as passive and active steps

Faster the change, further one has to look into possibilities in the future, the analogy given is that of driving at night and why one has to have to longer range headlamps for faster speeds [69]. Not all the TF techniques can be used for all forecasting projects [18]. Next 4 subsections will describe the stages of TF and the tools that can be used. The subsections will also highlight the areas of general application of the tools, the fields where the tool has been applied and some indicative strengths and weaknesses. The tools considered under each of these stages is the most cited TF tool (based on Google Scholar results from Slupinski's report [1]).

3.1 PEOPLE

The primary requirements for the people stage are:

1. The right people have to be selected for making a technology forecast,
2. Extent of coverage of all people,
3. The method of extraction of knowledge.

Thus, the classes of people to be included based on the above-listed criteria are:

a) Primary stakeholders,
b) Experts (Hands on and Technical),
c) Other stakeholders,
d) Principle users,
e) Lead designers,
f) Early adopter users.[1]

The people in the committee form the acronym PEOPLE. The list of classes of people is a suggested list and some others could be included, for example, policy makers and statesmen to diversify the list of people. As it has been suggested in section0 and 1.2, there are conditions where opinions from people are necessary and cases where the opinions and data can be obviated. Some of the potential activities that can be initiated in this stage are:

a) Extraction of problems with current technology,
b) User interviews,
c) Knowledge extraction of the state of the art of the technology to be forecast,
d) Simulation of the technology or recording usage of the actual technology.

Some other techniques that can also be used at this stage are surveys with weightages attributed to the parameters chosen. The parameters and the weightages have to be chosen by the classes of people described above. Once the initial effort of extracting information from the experts is taken, a graphic tool with potential forecasts mapped with probability of occurrence can be used to discover the prioritized list of problems to tackle.

3.2 Model

This is the stage in which models are built using some inputs from the PEOPLE stage. The actors involved in this stage are people building the model, experts who will provide inputs for building and verifying the model and R&D managers who will need to use the results. The modelling technique for building such a model can be chosen from the list of techniques outlined in Section 1.2. This stage will also require a choice of the correct model for usage for the entire technology forecasting activity. As discussed earlier, choosing more than one model for the purpose enhances accuracy and reliability of the TF. The recommendations and warnings mentioned in Section0 should be considered and included at this stage. The recommendations and warnings will serve as a checklist to make sure of the effectiveness of the choice of the final TF framework or model.

3.3 Course Correction (Passive)

Extracting knowledge from experts and obtaining models for the technology are essential in generating predictions for technology forecasts. If one is monitoring technology growth over years or is a professional forecaster interested in observing technology may need to adjust the predictions as time progresses. Typical people involved in this stage are: forecasters, investors who track technology progress and patent analysts monitoring a technology. Figure 4 shows that mathematical models may be inadequate to predict the trend after an innovation has been adopted, as was studied in mobile telephony diffusion studies [72]. There may be some factors that the initial forecasts excluded or there may be environmental factors that may have changed after the initial forecasts were made. This stage in the technology forecast is considered passive, since there is no action taken by the forecaster or by the technologists who monitor the technology. Some course correction tools indicated in literature are:

a) Imitation coefficients in growth curves [45],
b) Diffusion models – to track the diffusion of technology from innovators to early adopters to early majority to late majority [71],
c) Environmental monitoring – The 4 stages in this method are: i) Collect, ii) Screen, iii) Evaluate and iv) Threshold setting [56].

[1] Care should be taken in choosing the early adopters since they could be the “laggards” of the earlier technology generation, as summarized by Goldenberg and Oreg [74]

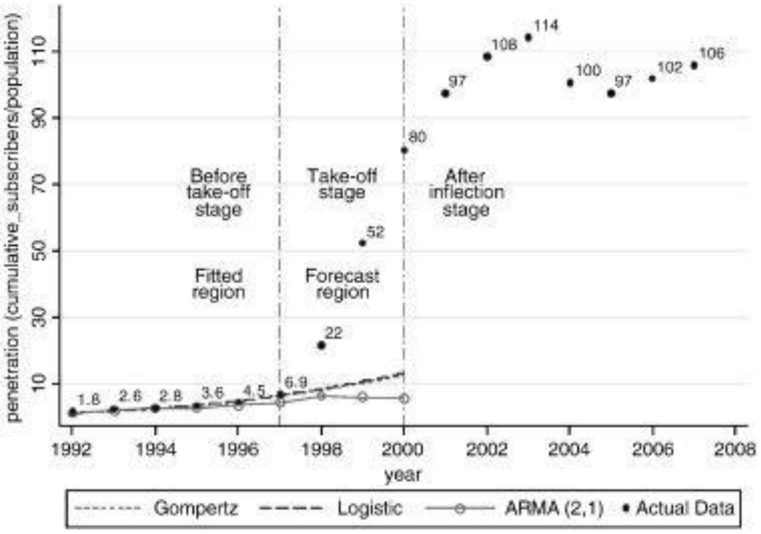

Figure 4 Mobile telephony diffusion studies conducted in Taiwan show the inadequacy of growth curves in predicting the take-off [72]

3.4 Impact Analysis (Active)

The models from earlier stages and their corrected versions deserve a model for communicating the model to the recipients of the forecasts along with a clear and unambiguous manual to explain the rationale behind the predictions. This stage is also meant for organizations, which are not only interested in generating the forecasts, but also are involved in implementing the technology or are players in the technology of interest. The people involved in this stage are: technology decision makers and planning managers. This stage also serves as a dipstick to measure progress on some of the forecasts.

Scenarios with storyboarding with clearly drawn scenes can be used at an organizational level to convey forecasts and action plans.

4. Conclusions

There were basic questions to answer about the initial steps of a TF activity – knowledge extraction from experts and building a model while keeping in mind that this has to be done under the ambit of manufacturing technologies. Another constraint to be added is that the end users of the FORMAT methodology will be R&D managers who will use the developed methodology as a support in decision making. The basic criteria for choosing experts for a TF activity were derived from literature. The awareness of the time and place to use the knowledge from the experts was also outlined. New industries and emerging technologies were areas where the experts' opinions were sought the most. Some dangers of relying on experts and potential pitfalls because of the over reliance was also described – tunnel vision, cognitive biases and lack of reference events.

In the area of modelling specifically for technology forecasting, there were several promising techniques that were described according to their usage in product or process modelling. There were recommendations and warning extracted from the analysis of widely cited TF tools. These recommendations and warnings were extracted in the context of requirements of TF for manufacturing technologies. Experts and building models were part of these requirements as well. Some common errors in technology forecasting were highlighted and found to be very important in both modelling and during knowledge extraction from experts. A note to make in these steps will be to assess the maturity of the technology. In actuality, most of the TF tools taken in consideration seem to have past applications for self sustaining or mature technologies and not emerging technologies.

A 4-stage model for technology forecasting is proposed on the basis of literature studies. The 4 stages are:

1) PEOPLE,
2) Model,
3) Course Correction (Passive),
4) Impact analysis (Active).

PEOPLE stage consists of features from Delphi and focus groups for knowledge extraction from experts and other important stakeholders. Model stage involves selection of a modelling technique, a model and imbibing the recommendations/warnings from the TF tools to augment the experiential models from the PEOPLE stage. Additionally, expert outlook is necessary for the building and interpretation of the model and will depend on the choice of the model(s). Course correction takes into account the changes in the initial forecasts arising from the PEOPLE and model stage. Alternatively, the course correction can be an inbuilt step in the model stage. However, attention has to be paid to the changes outside of the factors that have already been included in the model. Impact analysis includes an important procedure in an organization, which is communicating plans or forecasts across the organization. Moreover, the last stage is also a dipstick to measure the effectiveness of actions taken as a result of the forecasts.

Analysis of the tools measured against criteria required for the TF tools of manufacturing technologies revealed that there is no single technique that solves all the problems.

Overall, some features such as a survey-based method (from multi criteria analysis), multiple rounds of expert interaction (Delphi), written scenarios, graphic detail of a relevance tree and the extraction of parameters using mathematical modelling, can be used to develop a comprehensive model.

There are still some unanswered questions and uncovered territories in the purview of this study:

1. Why does modelling take so much of time or effort? This question is important since before a technology is taken up for forecasting, it is imperative to define the boundaries of the system and, hence, be aware of the environment around the system. If one has to get a complete system with all the relationships to the environment, the model-building activity could require dedicated time and effort. Is there a "good enough" point for the model that is built?
2. What are various mathematical modelling techniques that are available for technology forecasting? Are there standard criteria to analyze the applicability of these techniques for specific needs in the context of technology forecasting?
3. How many variables or factors does one need to include in a model, so that the forecasts are accurate? Is it 10 or 100 or 200? Also, implicit is the question – have all the relevant factors been accounted for?
4. A very similar question to the previous one, but with experts in mind – have all the relevant experts been included for knowledge extraction?
5. Has all the "tacit" knowledge been converted into explicit knowledge in the modelling stage?
6. How does the expert find out if they are indeed suffering from a bias? Is this awareness alone enough to reduce the negative effects of bias in a TF activity?
7. There are still a number of TF techniques that have to analyzed for recommendations and warnings (as described by Slupinski [1]), at least 90 or more techniques. The main constraint may be the effort and time involved in such a massive activity. The results will certainly be rewarding at the end of such an activity.
8. There may still be tacit knowledge of the usage of the TF tools with many of the experts in the world. A systematic Delphi-based study or face-to-face interviews of these experts will bring to light some features and case studies that have not been documented before.
9. A deeper literature study of learning curves and their use in expertise analysis in an organization is suggested.
10. Additionally, all the recommendations and warnings extracted in this report can be integrated into the 4-stage model proposed in Section 3.

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