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The Application of the IFM Framework and FIDD Method on an Industrial Cigarette Filter Maker

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Abstract: In seeking to retrofit decade old production systems, there is often the need to re-analyse many facets of the system as previous assessments and past assumptions must be validated or amended. The following paper presents the system modelling and analysis of an industrial cigarette filter maker. The matrix based Integrated Function Modelling (IFM) Framework was applied to model six design entities to create a comprehensive system understanding. The derived system model was subsequently analysed using the Function Integrity Diagnosis and Documentation (FIDD) method to identify risk to system function. Through the unique use-case discussed in this paper, new insights for improvement of the modelling approach and analysis method are identified. This paper concludes with actionable recommendations for improved application of the IFM Framework and FIDD method.

Keywords: Design structure matrix, integrated system modelling, design methods

1 Introduction

The continuous development and adaptation of technical systems is a prevalent activity among design engineers (Jarratt et al., 2011). A challenge in system adaptation is that many systems have been developed under technical assumptions made decades ago, and due to missing or incomplete documentation, these systems can only be marginally adapted to new requirements. Despite the value of thorough documentation to reuse findings of previous analyses (Roth et al., 2015), there is often a lack of traceable information regarding precise system function and their implementation. This can be attributed to delayed intervals between development phases and employee turnover in design engineering organisations. As a result of such inconsistent exchange of information, there is inherent necessity for monitoring accuracy and ensuring thoroughness of relevant system information (Chandrasegaran et al., 2013).

System modelling is an approach to manage past and emerging system design information (Buur and Andreasen, 1989). Various system models focus on different design entities, such as function (Hubka, 1984) or system architecture (Eppinger and Browning, 2012). Design engineers will routinely transition from one entity to another in their design activities, so it is important to be able to integrate multiple entities (Aurisicchio et al., 2013). An example of a modelling approach that can systematically model a multitude of entities is the Integrated Function Modelling (IFM) Framework (Eisenbart et al., 2017). Because of its utility in enabling comprehensive system understanding, the IFM Framework has since been extended with the Function Integrity Diagnosis and

Documentation (FIDD) method for risk identification (Wichmann et al., 2018). The IFM Framework, in combination with the FIDD method, provide potential to analyse multifaceted systems and thereby compensate the losses of information that may occur over a delayed period of development. It is the objective of this paper to apply these two approaches to model and analyse a decades old industrial production system.

The IFM Framework has been previously applied in rather theoretical contexts to analyse systems such as a coffee machine and a glue gun (Eisenbart et al., 2015; Gericke and Eisenbart, 2017). This paper seeks to apply the IFM Framework on an industrial production system. This will not only expand the context of application but also the system will be distinct in its production process. Where the use-case of a coffee machine has an end state (coffee is made), the use-case of a production system is essentially an endless process of manufacturing. For production systems this creates a clear distinction as process functions can have reciprocal dependencies leading to uncertain consequences should any function fail. To apprehend any risk of function failure, this analysis was complemented with applying the FIDD method.

This paper continues with Section 2 to explain the IFM Framework and the FIDD method. Section 3 describes a use-case on an industrial cigarette filter maker. Section 4 offers a discussion of the modelling and analysis approach. Recommendations for improvement and conclusions are presented in Section 5.

2 Combining Function Modelling and Risk Assessment

2.1 The Integrated Function Modelling Framework

The IFM Framework applies multiple design matrices (MDM) (see Eichinger et al., 2006 or Kreimeyer and Lindemann, 2011) to model six design entities (such as use-case, state change, system actors, etc.) into one centralised Integrated Function (IF) model. These entities are individually modelled in a matrix and arranged in a modular framework of six different *views* as illustrated in Figure 1. The incorporated views are the use-case view, process flow view, effect view, state (change) view, actor view and interaction view (see Eisenbart et al., 2017). The number of included views and their arrangement in a framework is to the discretion of the design engineer. However, the proposed arrangement follows a systematic ontology and striving for model thoroughness is significant for comprehensive insight

The centralised modelling of multiple design entities makes the design information more accessible and enables model refinement without having to switch to alternative models (Eisenbart et al., 2015). The matrix-based representation creates a helpful self-check for accuracy as design engineers can visually cross reference a modelled entity with another entity. This improves the traceability of system relations among the design entities and the modelling of emergent realisations. Thus, it supports the modelling process of the design engineer and improves the system understanding as the perspective is widened with multiple views.

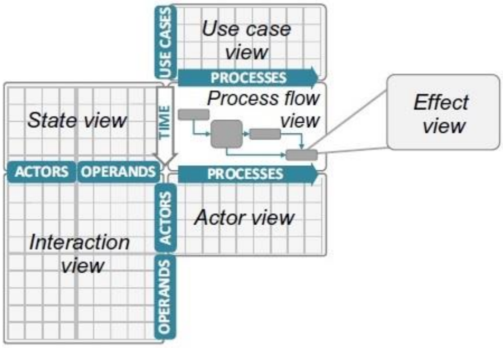
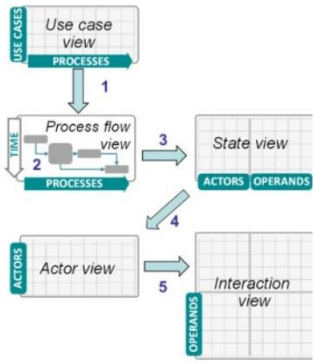


Figure 1. Integrated Function Modelling framework (Eisenbart et al., 2017)

2.2 The Function Integrity Diagnosis and Documentation Method

The FIDD method can support risk management activities, in particular risk identification and assessment (Wichmann et al., 2018). The proposed method prescribes an approach for diagnosis of an IF model and as such, is a practical extension to the IFM Framework. In applying this method, the modelled entities of the individual views of the IFM Framework are diagnosed for technical risk in a systematic order of seven steps, illustrated in Figure 2. A result of the FIDD method seeks to identify a multitude of potential risks to function and document these as failure modes. Each of these failure modes is individually assessed and allocated a risk priority number (RPN) as the product of an ordinally rated severity (S), probability (P) and likelihood of detection (D). A completed assessment provides insight into the function integrity (risk to function fulfilment) of a system thereby informing mitigation activities and design decision-making (Wichmann et al., 2020).

1. Negate or reformulate the *use-case* into an undesirable event.
2. List the *transformation processes* from upstream to down-stream as undesirable events.
3. For each transformation process list the *state-change* as incomplete.
4. For each incomplete state-change list all *affecting actors* and operands.
5. For each affecting actor, list all *interactions* in the interaction view.
6. Question the integrity of the documented constellation and list the failure consequence
7. For each failure consequence list the possible failure mode.



1	2	3	4	5	6	7	Current Situation			
Potential Failure Mode (Use Case)	Potential Failure Mode (Transformation Process)	Potential Failure Mode (State Change)	Potential Failure Mode (Affecting Actos)	System Interaction (DSM)	Failure Consequence	Failure Mode	S	P	D	RPN

Figure 2. Analysing an IF model with the FIDD method (Wichmann et al., 2018)

3 Use-Case in a Rod Filter Maker

This research applied the IFM Framework and FIDD method on a production system manufacturing cigarette filter rods. The Rod Filter Maker manufactures several thousand filter rods per minute and will be defined as an endless production system. A (cigarette) filter consists mainly out of a filter material which is wrapped in filter paper and glued together with an adhesive. For the manufacture of such a filter, the initial product is an endless filter strand which is subsequently cut to an appropriate filter length. A schematic of the manufacture of filter rods is illustrated in Figure 3.

The Rod Filter Maker is distinguished into three areas. The first area is for material introduction, where filter material and paper are fed (introduced) into the production system (Figure 3-A). The second area is for material processing where the material is shaped cylindrically (Figure 3-B). The final area is for material transport, with a rotating conveyor belt (Figure 3-C).

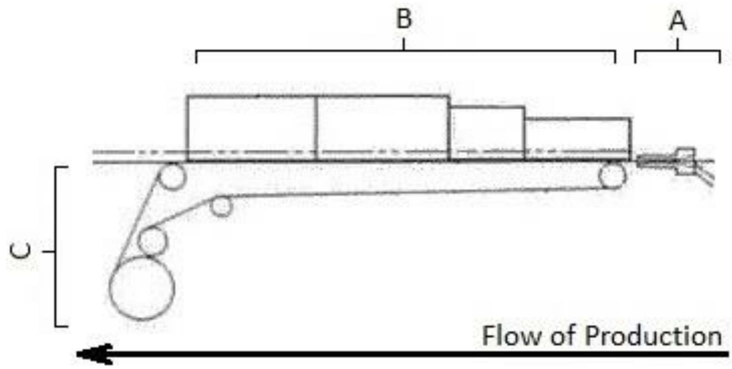


Figure 3. Diagram of a Rod Filter Maker with three sections; A: Leading of materials; B: Processing of materials; C: Transporting materials (after Sgrignuoli and Sartoni, 2016)

The functional requirements of the Rod Filter Maker reflect the need of a precise filter diameter and uniform surface quality. There is a challenge in manufacturing the filter strand as it is important to manage the friction among the workpieces within the production system, illustrated in Figure 4. Inside the Rod Filter Maker, the strand of filter material is guided between an upper form (Figure 4-1) and a lower form (Figure 4-5) which due to their round contours, shape the filter strand to become cylindrical. During manufacturing, the conveyor belt (Figure 4-3) is subject to wear from the continuous contact and friction as it transports the material. This wear is intensified with the internal pressure of the compressed filter material. The thickness of the conveyor belt has consequential effect on the quality of the manufactured filter strand because of its direct contact. With the wear of the conveyor belt, even small form variances are directly imparted on the filter strand leading to dimensional deviations in shape and size. Currently these deviations are compensated through a vertical shift of the upper form (Figure 4-1). The design challenge is to preserve filter quality with pervasive wear and friction of the conveyor belt.

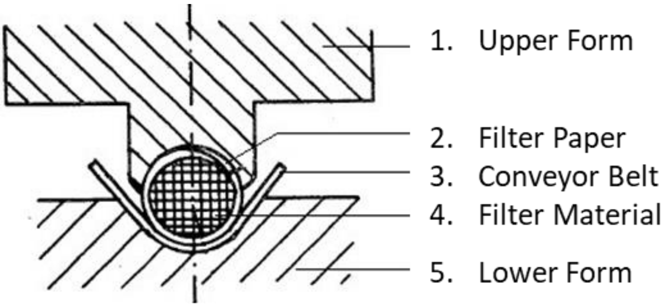


Figure 4. Diagram of interior cross-section of Area B (after Boegli et al., 1970)

4 Discussing the IFM Framework and FIDD Method

4.1 Application of the IFM Framework

An IF model of the production system, Rod Filter Maker, was created, refined and analysed over the course of 2 months. The development of the model began with initial considerations focusing on the use-case and process model. Continuous refinement added design information to accumulate toward a comprehensive IF model. The original IF model encompassed a complete DIN A0 and has therefore been abbreviated to its essential insight and illustrated in Figure 5.

The present production system was challenging to model as the endless production process hinders the definition of a clear process sequence. Where some production processes have a sequential process flow, in an endless production system the processes can have retroactive effects. Furthermore, in this production system, the operands and their function are given particular emphasis as system actors are passive in the process flow.

Over repeated iterations, the number of identified processes increases, and the design engineer must define a system boundary. This is important to ensure the model still elucidates insight before becoming too complex in scope. The system boundary determines what design elements are in/excluded in the given IF model. One strategy for managing complexity in using the IFM Framework is distinguishing alternative use-cases. As a production system intended for mass production of filters, there were three additional use-cases identified. These alternative use-cases are assembly, calibration, and maintenance. There is sufficient similarity among these use-cases (in involved processes and identical state changes) that they can be readily summarised into one use-case without losing valuable insight. On the other hand, this does not apply to the use-case production.

Many sources of information exist that can be used to derive an IF model. The design engineer can investigate existing CAD models, requirements lists, completed risk assessments and have discussions with participating design engineers to gather other empirical information. The IFM Framework essentially provides instructions for how a user can systematically understand a technical system from multiple perspectives. Adding content (i.e. a design entity) to any of the views of the IFM Framework leads to adding of information in another view, thereby creating a flow of information and development of a consistent IF model. This effect ensures that every modelled entity is cross referenced for its accuracy by another entity. Therefore, as the IFM Framework prompts design engineers to model relevant information that they would not have originally considered, it effectively reduces discipline related silo-thinking. Additionally, the information cycle and the inherent iterations lead to increased system understanding as the system is addressed from multiple perspectives to model multiple design entities in detail.

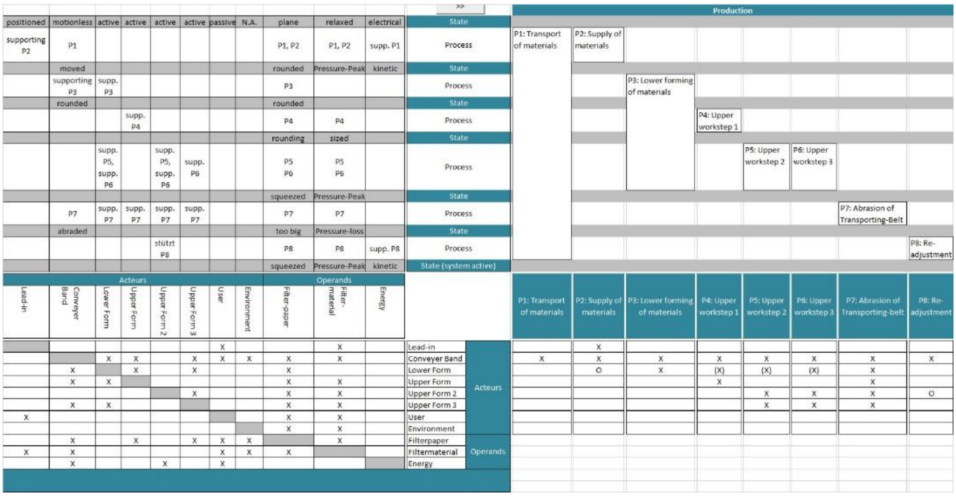


Figure 5. Abbreviated IF Model for a Filter Maker within the use-case "production"

4.2 Potential for Improving the IFM Framework

Through modelling the Rod Filter Maker, this research identified potential for improving the application of the IFM Framework. In the process-flow view, the dependencies and sequence of individual processes are modelled. However, there is no explicit definition of continuous flow, small intervals, or delayed pauses that document how a process flows to another process. In reading musical notes, it is said, the musician also has to *play the pauses* between the notes. The design engineer must therefore explicitly model or give indication about the process between processes. In some cases, and particularly in mass manufacturing, there are significant effects within these pauses.

To capture insight from within these pauses, there is potential to extend the process-flow view of the IFM Framework with a micro and a macro perspective. A macro-view could show the general overarching process-flow and a micro-view could show more detail when needed. This extra detail could emphasis sub-processes to enable more in-depth analysis. Even a relatively simple indication in the macro-view would be enough to raise awareness of such pauses and two examples are given in Figure 6. A micro-view could then focus on these pauses or model these as active functions.

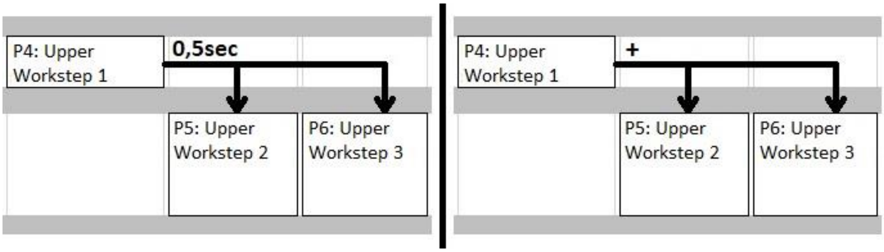


Figure 6. Two examples for visualising timed intervals between processes

Another consideration to precisely understand system function requires more detail in the state view. To identify system flaws, a system state must be modelled beyond an intended state and extended with a likely actual state (i.e. an is-state). The definition of the intended state will be validated through the information cycle of the IF model. A reversal of thought is often helpful to define an actual state. Take for example the form of the filter paper wrapped around the filter material which can be theoretically defined as "round" and "sealed". However, documenting the states as "rounding" and "sealing" allows more room for interpretation as to the state of the filter contour but implies a wrapping process at different degrees of roundness (i.e. not the ideal cylindrical shape).

Furthermore, in modelling a system using the IFM Framework, design flaws and weaknesses can be identified. If no immediate mitigation occurs, then these flaws are usually confirmed with greater insight in the subsequent analysis with the FIDD method. An example of a possible design weakness becoming apparent through system modelling is when two concurrent processes influence a state change counteractively.

4.3 Potential for Improving the FIDD Method

This research proposes an altered sequence in applying the FIDD method. The alteration occurs when the actor view is referenced after the state view. The conventional sequence by Wichmann et al. (2018) goes from use-case view, to process-flow view, to state-view, to the actor view and ends with the interaction view. However, this sequence is inadequate in analysing an endless production process as this leads to repetitive causality chains.

In analysing an endless production system, system operands are placed into higher focus than system actors requiring the FIDD method to be adapted for a clearer focus on operands. This means that in one use-case, the processes are analysed sequentially and defined as negative undesirable events. Next, for each process, the intended state is documented as unfulfilled. Subsequently the involved actors/operands of the relevant state change are listed as having experienced a possible failure.

In the adapted approach the essential difference is that, the actors/operands are not selected from the actor view, rather they are identified from the interaction view, slightly changing the sequence of analysis. In this sequence, all actors in direct involvement to the state change are listed. Any actors/operands not involved in an interaction are not listed. In this case the failure mode relates to the state of the involved actor and reflect the definition of the undesirable event. The failure mode relates to the flawed interaction among involved actors, meaning a processing failure can be traced back to a failure such as in calibration, material or construction. The altered sequence is illustrated in Figure 7.

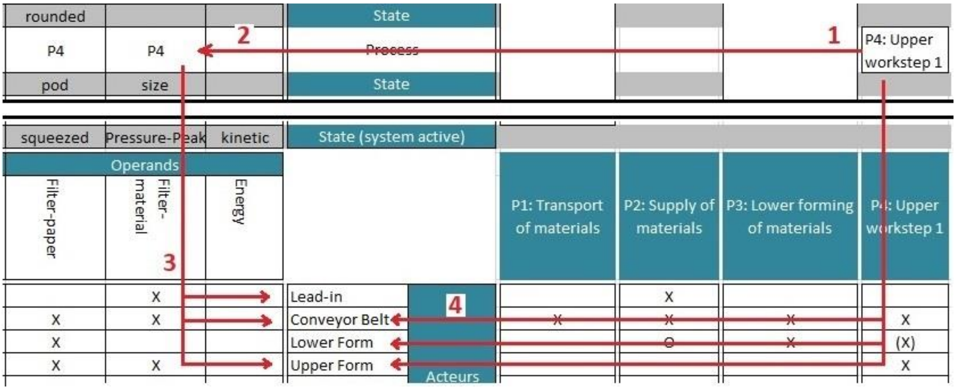


Figure 7. Adapted Sequence of FIDD Method for Operand-based FIDD results

Additionally, in analysing system state changes, Wichmann et al. (2018) propose to define state changes as undesirable events or as an unachieved state change. Similar to the discussion of state changes in Section 4.2, an unachieved state change only offers a partial insight in risk identification. Following this approach there is no consideration to the different degrees of how a state change has been (un)fulfilled. For example, consider the heating of water from cold to hot. This leap in temperature, i.e. the state change, leaves a range of states unaccounted for, such as any degree of warm water. With such a limited perspective there is possibility to miss several possible failure modes. As such, it is advisable to extend the definition of state changes to encompass a greater range in possible system states. This is emphasised by Figure 8, which lists a sample of identified failure modes of the Rod Filter Maker. In Column 2, the definition of an "undesirable event" immediately allows the identification that the parallel processes P5 and P6 are counterproductive in achieving an intended state change. Furthermore, with the higher focus on the operands (as described above), Column 3 visualizes that these two processes involve the same operand (Filter Material). These newly identified risks were decisive for risk mitigation activities and the subsequent system improvement.

Potential Failure Mode (Transformation Process)	Potential Failure Mode (State Change)	Potential Failure Mode (State Actor)	System Interaction	Failure Consequence	Failure Mode	S	P	D	RPN
P5: Upper workstep 2 faulty	low pressure	Filter material	Upper form 2	Bigger sized Product-diameter	Bigger sized working-diameter	8	2	2	32
			Conveyor Belt	Loss of binding capacity	Decreased Thickness	10	2	2	40
P6: Upper workstep 3 faulty	high pressure	Filter material	Upper form 2	pressure mark	Smaller sized working-diameter	8	2	2	32
			-	loss of form	Loss of position	9	4	4	144
			Conveyor Belt	pressure mark	increased Thickness	10	2	2	40
			Upper form 3	Bigger sized Product-diameter	Bigger sized working-diameter	8	2	2	32

Figure 8. Sample of FIDD results

5 Conclusion

This paper presented a use-case which applied the IFM Framework and the FIDD method to model and analyse an industrial cigarette filter maker. This production system was developed decades ago and has long gone without improvement or retrofitting. Because the documentation of previous assessments and implicit assumptions about the functionality of the system were incomplete or unavailable, the system was reanalysed. In addition to identifying means of improving the sub-system Rod Filter Maker, the authors determined four recommendations for the improved application of the modelling approach and analysis method.

It was identified that there is need to provide a macro and micro view within the process flow view of the IFM Framework. This would signify the process between processes and prevent the disregard of significant effects. A second recommendation for the IFM Framework is in modelling system state changes. The current approach only seeks to model the intended states of a system. This should be extended with incorporating a greater range of possible system states to capture different degrees of a state change.

The FIDD method can also be similarly improved in its analysis of state changes. Rather than focusing only on the fulfilment of a state change, the documentation of a state change should be reformulated as an undesirable event. Furthermore, this paper proposes an alternative sequence in performing the FIDD method. The original sequence was developed for processes with a starting and end-state. The new sequence is likely more appropriate for an endless production process which focusses more on system operands. Further research will build on these recommendations to pursue further improvement in the design method.

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