The Evolution of Functional Systems Modelling

From Purposeful Inquiry to Data-Linked Models of Emergent System Behaviour

David Slater

Introduction

Functional abstraction-based Modelling is a logical approach and powerful way of representing systems through the functions required to produce their behaviour, the conditions and flows that connect those functions, and the interactions through which intended, degraded, adaptive and emergent outcomes arise. It is not presented as a previously established school of systems thought. Rather, it is a retrospective synthesis that draws together compatible ideas from general system theory, cybernetics, organisational systems thinking, engineering functional modelling, socio-technical systems, system dynamics, safety science, resilience engineering and the Functional Resonance Analysis Method.

The value of such a synthesis lies in its ability to connect forms of modelling that are too often treated separately. Some traditions begin with purpose, perspective and boundary. Others begin with technical functions, transformations and interfaces. Cybernetic approaches focus on feedback and regulation, while dynamic approaches seek to explain behaviour over time. Contemporary safety and resilience methods add constraints, adaptation, performance variability and emergence. IFSM does not erase these differences. It provides a common architecture in which their distinct contributions can be related.

A converging intellectual lineage

The development of functional systems thinking did not proceed through a single historical line. General system theory challenged the reduction of a system to an inventory of independent components and emphasised organised wholes, open-system exchange and relationships with the environment (von Bertalanffy, 1968). Cybernetics added circular causation, communication, feedback and regulation (Wiener, 1948; Ashby, 1956). These developments shifted attention from what a system is made of towards how it maintains patterns of behaviour under changing conditions.

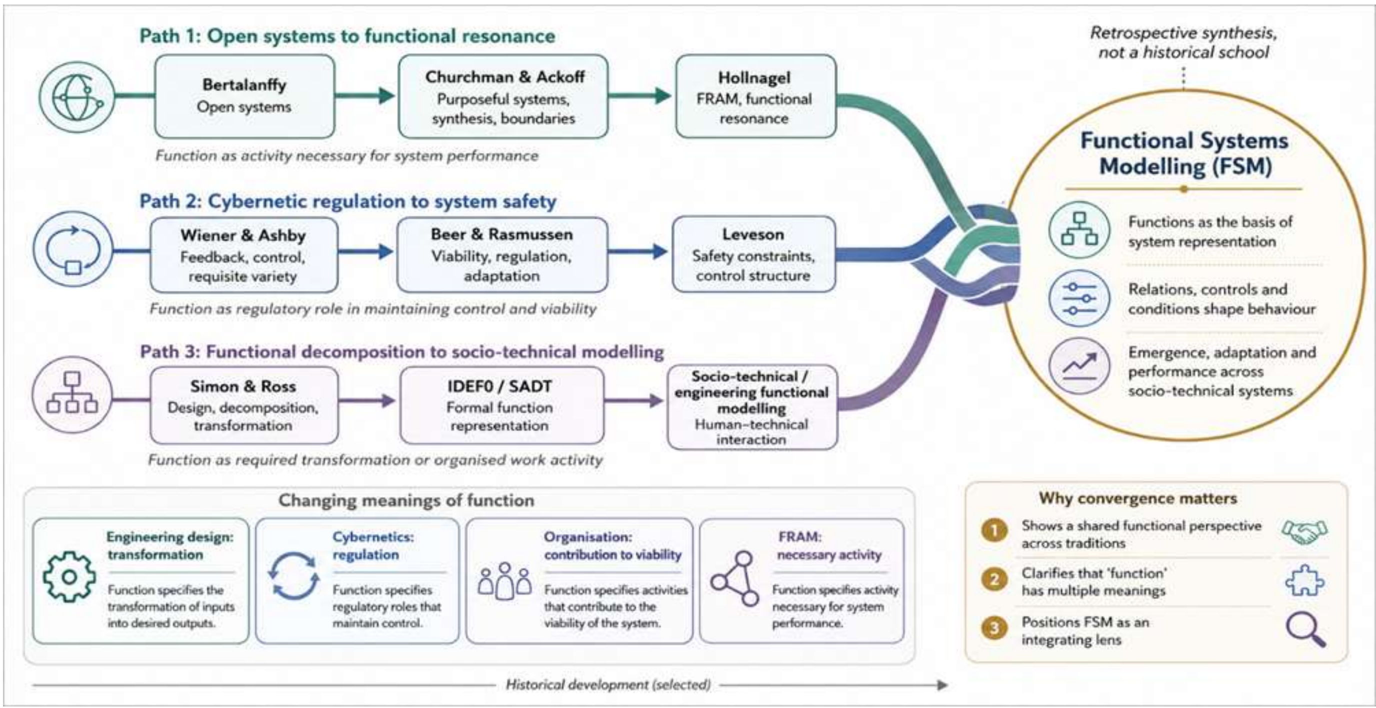
Churchman and Ackoff extended systems thinking into purposeful human and organisational settings. Their work stressed that systems are defined partly through purposes, choices, boundaries and the interests of those affected by them. Ackoff's treatment of organisations as purposeful systems also challenged the assumption that complex problems can be solved by decomposing them into independently manageable parts (Churchman, 1968; Ackoff, 1971, 1974). Stafford Beer developed a complementary organisational cybernetics in which viability depends on a recursively organised set of operational, coordinating, controlling, intelligence and policy functions (Beer, 1972, 1979, 1985).

The socio-technical tradition developed by Trist, Bamforth, Emery and their colleagues added another essential premise: the social and technical arrangements of work are mutually constitutive and cannot reliably be optimised in isolation (Trist and Bamforth, 1951; Trist, 1981). Checkland's Soft Systems Methodology then addressed situations in which even the nature of the system, its purpose and the relevant measures of improvement are disputed. In SSM, models of purposeful human activity are devices for disciplined inquiry and learning, not claims to be neutral replicas of reality (Checkland, 1981; Checkland and Scholes, 1990).

Engineering design and functional modelling contributed greater representational precision. In methods such as SADT and IDEF0, a system is modelled in terms of the activities it must perform and the inputs, controls, outputs and mechanisms associated with them. IDEF0 explicitly distinguishes the functional perspective from the particular organisational or physical arrangements through which functions are realised (NIST, 1993). System dynamics added stocks, flows, feedback loops, non-linearity and delays, enabling the mechanisms producing behaviour over time to be represented and simulated (Forrester, 1961; Sterman, 2000).

Modern safety science extended the systems perspective further. Rasmussen represented safety as an outcome of interacting decisions across multiple levels of a socio-technical system and described how work may migrate towards boundaries under competing pressures (Rasmussen, 1997). Leveson's STAMP treats safety as an emergent property maintained through constraints within hierarchical and distributed control structures, rather than as the simple consequence of reliable components (Leveson, 2004, 2011). Hollnagel's FRAM represents the functions necessary for everyday performance and examines how variability in their outputs may combine or resonate to produce both successful and unwanted outcomes (Hollnagel, 2012, 2018).

IFSM[1] emerges from this convergence. General system theory supplies organised wholeness; cybernetics supplies feedback and regulation; organisational systems thinking supplies purpose and viability; engineering design supplies functional representation; socio-technical systems supply the inseparability of people and technology; system dynamics supplies behaviour over time; and contemporary safety and resilience approaches supply constraints, adaptation, variability and emergence.



The changing meaning of function

The word **function** does not have exactly the same meaning across these traditions. In engineering design, a function is commonly a required transformation: something the system must do to convert specified inputs into desired outputs. In cybernetics, function is more often a

[1] *IFSM (Interactive Functional System Modelling), is suggested as an acronym to help define this concept as an overarching evolved modelling approach.*

regulatory role, such as sensing, comparison, communication or action in the maintenance of a controlled condition. In organisational systems thinking, a function is understood through the contribution it makes to purpose, coordination or viability. In FRAM, a function is an abstract representation of an activity necessary for system performance, regardless of whether that activity is performed by people, technology or an organisation.

These meanings are related, but they are not interchangeable. Engineering asks what transformation is required. Cybernetics asks what must sense, compare or regulate. Organisational theory asks what contribution sustains the viability or purpose of the whole. FRAM asks what activities are necessary, what conditions enable them, what outputs they produce and how variability in those outputs affects other activities.

IFSM therefore adopts a deliberately inclusive but explicit definition:

A function is a process, activity or regulatory contribution through which system states are transformed, coordinated, maintained or communicated.

Individual models should state which of these meanings is being applied. This avoids treating transformation, regulation, organisational contribution and performed activity as if they were identical concepts.

A foundational definition of a functional system

In IFSM, a system is defined provisionally as a dynamically bounded organisation of interacting and interdependent functions whose collective activity produces, regulates and sustains an identifiable pattern of behaviour.
A minimal representation is:

$S=\{F,X,B,E\}$
where (F) is the set of interacting functions, (X) represents internal states, (E) represents external states, and (B) represents the interface states mediating their interaction.

Where a genuine Markov-blanket relation can be justified, the internal and external states satisfy:

$X \perp E \mid B$
The expression means that internal and external states are conditionally independent when the blanket states are known. In active-inference formulations, the blanket is commonly partitioned into sensory states, through which external conditions affect the system, and active states, through which the system affects its environment (Kirchhoff et al., 2018).

This is more than a line drawn around a convenient object. A Markov blanket is a formal statistical relationship among states. Its use in IFSM should therefore be treated as a modelling hypothesis: the analyst proposes that the relevant internal and external dependencies are mediated through identifiable interface states and then seeks evidence that this is a useful and defensible representation.

For less formal applications, the language of **receptive and active interfaces** may be preferable. A system receives material, energy, information and constraints through receptive interfaces and alters its surroundings through active interfaces. The Markov-blanket formulation then provides the more rigorous special case in which the required conditional-independence structure can be demonstrated or reasonably approximated.

FRAM as the Crucial Link in the Emergence of Functional Systems Modelling

FRAM occupies a pivotal position in the convergence of the modelling traditions that lead towards Integrated Functional Systems Modelling. Earlier functional methods had already represented systems in terms of activities, transformations and flows, while cybernetics had emphasised feedback, regulation and control. FRAM's distinctive contribution was to make the function the central unit of analysis in complex socio-technical systems: not a passive box in a process diagram, but an activity that must occur, under particular conditions, and whose output may influence the performance of other activities.

The familiar FRAM hexagon is therefore much more than a graphical device. By placing the Output at one corner and the five receptive or conditioning aspects—Input, Precondition, Resource, Control and Time—around the remaining corners, the notation provides a disciplined scaffold for thinking about how a function is enabled, constrained, resourced, regulated and temporally situated. This is a crucial step beyond ordinary boxes and arrows. A box-and-arrow diagram can easily imply a simple linear flow, whereas the FRAM hexagon asks the modeller to consider the multiple ways in which one activity may depend on others. It helps users construct an interactive functional model rather than a sequence diagram.

This scaffolding is one of FRAM's great practical strengths. It helps analysts, especially those new to functional modelling, ask better questions. What has to be present before this activity can occur? What resources does it depend on? What controls or guides it? Is timing significant? What output does it produce, and where does that output become relevant elsewhere? In this sense, FRAM provides a structured grammar for describing functional interdependence. It prevents the modeller from moving too quickly from observed events to presumed causes and instead encourages attention to the conditions that make normal performance possible.

At the same time, the IFSM argument allows FRAM to be generalised. In a more computational functional systems model, the active function need not be restricted to five separate categories of non-output aspect. At a formal level, a function requires inputs, internal state and activation conditions in order to generate outputs. Some of those inputs may represent ordinary material, informational or energetic flows. Others may represent what FRAM calls controls, preconditions, resources or time constraints. In an executable implementation, these distinctions can be retained semantically while being encoded as typed inputs, metadata fields, thresholds, equations or activation rules.

This is where FMV and FMI become especially important. The FRAM Model Visualiser supports the construction and visualisation of coupled functions, while the FRAM Model Interpreter and metadata facilities point towards a more executable interpretation of functional models. Metadata can be attached to functions and aspects; equations can calculate values as functions are activated; and special keys or logical conditions can determine whether a function fires, holds, branches or produces a particular output. In such a model, a precondition is no longer merely a label on a hexagon. It can become a computable condition. A resource can become a quantified availability. A control can become a parameter or constraint. A time aspect can become an activation window, delay or sequence condition.

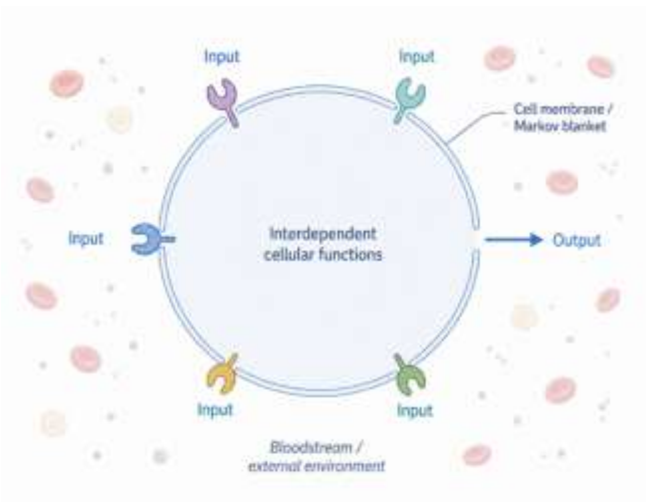
This does not make the original FRAM notation obsolete. On the contrary, FRAM is the bridge that makes the transition understandable. It gives users a way to move from narrative descriptions of work to structured functional interdependence, and from there towards data-linked or executable models. The hexagon is valuable because it teaches the modeller what kinds of dependency to look for. The more general IFSM implementation then allows those dependencies to be represented with greater freedom, precision and computational flexibility.

One way of expressing the relationship is to say that FRAM provides the scaffold, while IFSM provides the general architecture. FRAM helps the analyst learn to see systems as interacting functions rather than components, events or linear steps. IFSM takes that insight and abstracts it further: any active function may receive typed inputs, evaluate internal and boundary conditions, update its state and generate outputs that condition other functions. The familiar FRAM aspects remain conceptually useful, but they no longer have to be treated as fixed graphical categories. They can be translated into whatever formal representation is needed for the modelling purpose.

The analogy with “painting by numbers” is helpful if used carefully. Basic FRAM gives the modeller a structured pattern to follow, reducing the risk of overlooking important dependencies and making the construction of a viable model more accessible. Full IFSM allows greater freedom but also demands greater discipline. Once the predefined aspect categories are relaxed, the modeller must specify explicitly how inputs are typed, how activation conditions are evaluated, how metadata are propagated, and how outputs are calculated. The gain is computational power and modelling flexibility; the risk is that semantic clarity may be lost unless the modelling rules are made explicit.

FRAM is therefore not simply one method among many in the evolution towards Functional Systems Modelling. It is the crucial hinge. It converts functional modelling from a representation of arranged activities into a representation of active, coupled, variable performance. It shows how functions can be linked without reducing them to mechanical sequences. It provides a practical notation for building viable models of complex work. And, when coupled with metadata, equations and interpretation cycles, it opens the path from qualitative socio-technical modelling to executable functional systems modelling.

The cell as an archetypal example



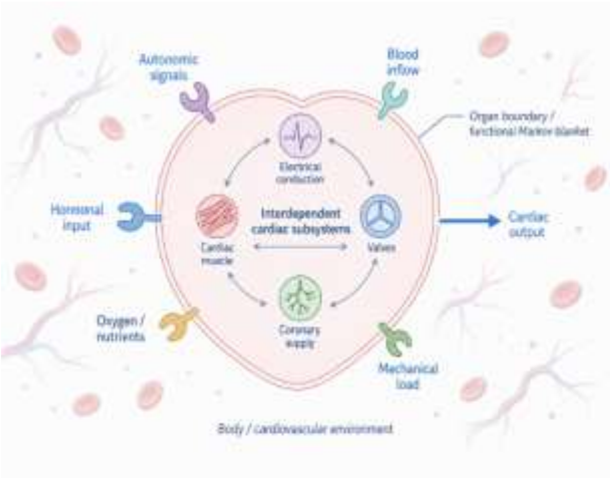
A cell suspended in the bloodstream provides an intuitive starting point. It contains interacting functions concerned with metabolism, signalling, energy conversion, regulation, repair and reproduction. Its plasma membrane separates the intracellular organisation from the surrounding fluid while simultaneously enabling controlled exchange.

The membrane should not be regarded merely as a passive wall. Receptors, channels, pumps, transporters and surface proteins mediate what the cell senses, admits, excludes and releases. The cell is therefore not defined through isolation, but through regulated interaction with its environment. Its internal functions sustain the membrane and its transport processes, while those boundary processes supply the materials and information needed to sustain internal organisation.

The example brings together the different meanings of function. Transport performs transformation. Receptors and signalling pathways perform regulatory roles. Metabolism and repair contribute to viability. The continuing activity of the cell depends on the interaction of all these functions.

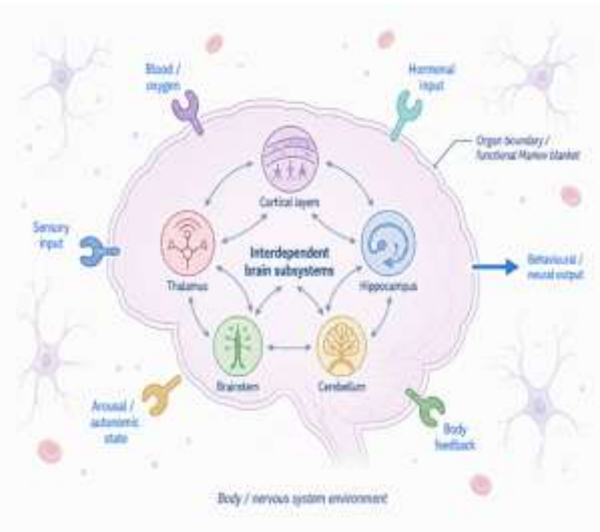
The cell membrane is an instructive physical analogue of a Markov blanket, although the two should not be treated as automatically identical. The relevant statistical blanket would consist of those membrane and boundary states that mediate the dependencies between intracellular and extracellular states.

Recursive organisation: from cells to patients



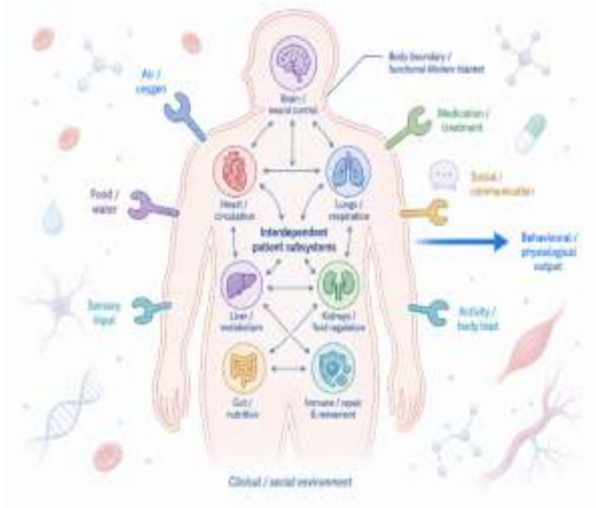
Functional organisation recurs across biological levels. Cells form tissues; tissues form organs; organs interact within the organism; and the organism interacts with a physical, clinical and social environment. This is best described as **recursive or scale-recurrent functional organisation**. The term *fractal* may be used metaphorically, but mathematical fractality should technically not be claimed unless formal self-similarity has been demonstrated.

The heart provides the first escalation from the cellular example. It is a nested functional system composed of specialised muscle cells, pacemaker and conduction tissues, valves, chambers, coronary circulation and regulatory connections. Their coordinated interaction produces the organ-level function of rhythmic and directed blood flow. This function cannot be attributed to any single cell or tissue type.



The brain represents a further increase in organisational complexity. It consists of large populations of neurons and supporting glial cells organised into recurrently interacting circuits, layers, nuclei and regions. Perception, memory, coordination, regulation and behaviour arise from distributed interactions across these structures rather than from one anatomically isolated centre.

At the level of the patient, the biological subsystems concerned with circulation, respiration, metabolism, renal regulation, immunity, endocrine coordination, movement and neural control are continuously interdependent. A disturbance in one subsystem may propagate through blood flow, oxygen delivery, metabolic products, neural signalling or hormonal regulation and become visible as a whole-patient condition.

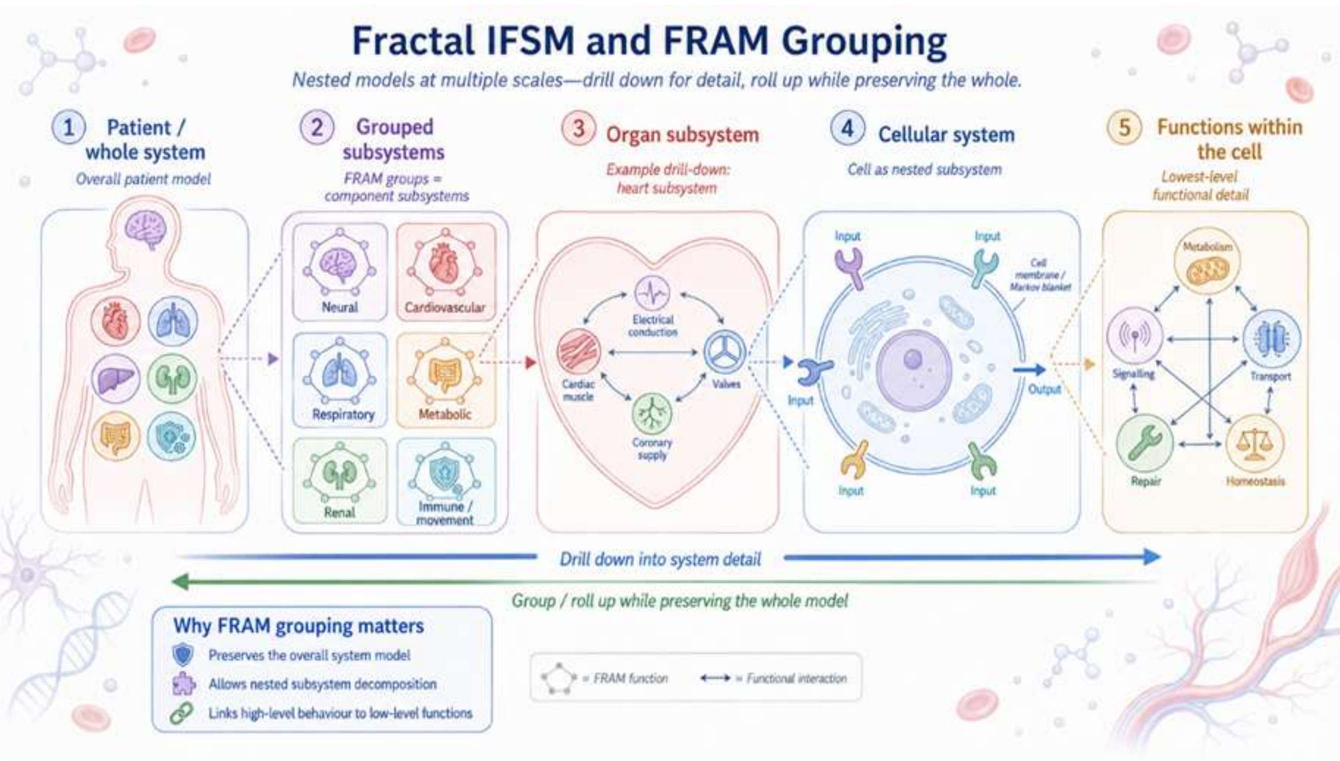


The patient is also more than an assembly of organs. Perception, cognition, communication, action and social participation are part of the functional system. In clinical work, the patient is nested within a wider care system that includes professionals, monitoring technologies, medicines, family members, information systems and organisational conditions.

This yields a central IFSM proposition:

A functional system may contain lower-level functional systems while simultaneously contributing as a function or subsystem within a larger functional system.

FRAM is particularly useful in this context because functions can be organised into groups representing tissues, organs, technical assemblies or operational domains. The modeller can examine local detail while retaining the couplings through which the grouped subsystem participates in the wider system. Grouping does not by itself prove a fractal structure, but it supports recursive decomposition and recomposition.



Extending the model into Safety Situations

The same reasoning can be applied to a highly complex operational setting. In aviation a safe flight is achieved by the successful interaction of several distinguishable technical, human and organisational systems embedded in a shared environment.

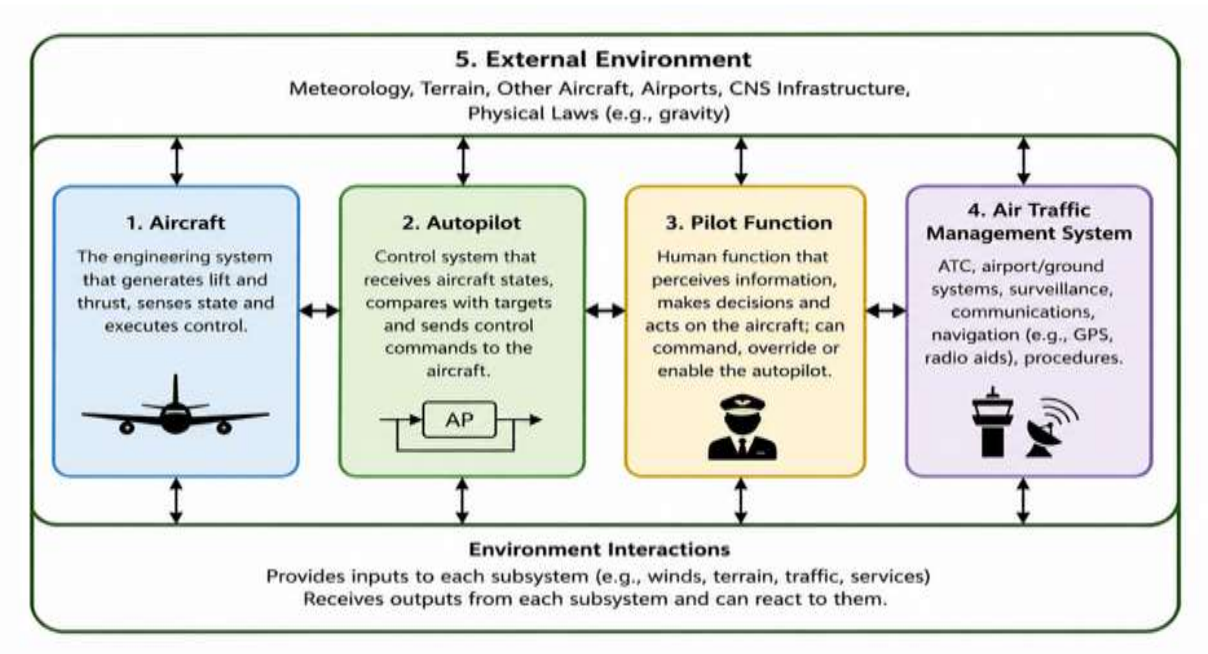
The first system of interest is the aircraft. It contains the interacting engineering functions needed to generate lift and thrust, maintain structural integrity, distribute energy, sense aircraft state, control attitude and trajectory, and manage configuration. It is an open technological system: flight depends on continuing interaction with airflow, gravity, fuel or electrical energy, control commands and environmental conditions.

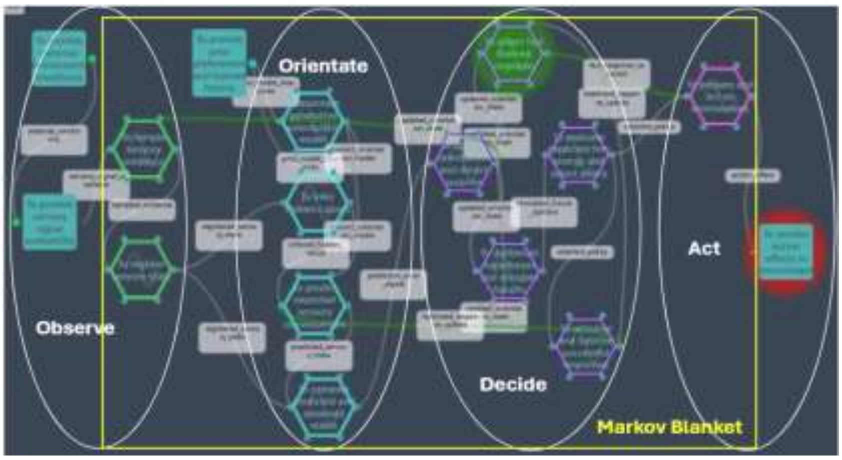
The second system of interest is the automatic flight-control system. The autopilot receives selected measurements of aircraft state, compares them with commanded targets and transmits control demands to flight-control computers and actuators. Aircraft motion changes in response, and the resulting state is sensed again. Aircraft and autopilot therefore form a closed feedback loop.

The third system of interest is the pilot function, defined independently of which individual crew members perform particular activities. The pilot function receives information through instruments, displays, warnings, visual cues, radio communication and bodily perception. It interprets the situation and acts through flight controls, thrust controls, mode selectors and other cockpit interfaces.

The pilot also supervises the automation. The function may select targets and modes, engage or disengage the autopilot, alter its instructions, take manual control or override automated behaviour. The pilot is therefore an adaptive controller of both the aircraft and its automated control systems.

The fourth system is the wider air traffic management and navigation system. It includes controllers, procedures, surveillance, communication, airport surface management and navigation infrastructure. GPS, radio-navigation aids, ADS-B, radar and instrument-landing systems are better understood as elements of the wider communication, navigation and surveillance environment than as components of ATC alone.





A possible FRAM/FSM model of the Pilot Decision system functions

These systems are embedded in an operational environment that includes meteorology, terrain, airports, airspace, other aircraft and the supporting technical infrastructure. The environment is not uniformly passive. Weather and terrain impose conditions, whereas other aircraft, controllers and ground systems are active entities capable of sensing and responding.

This is appropriately described as a **coupled multi-system socio-technical environment**. Some parts, particularly air traffic management and independently operated aircraft, may satisfy stricter definitions of a system of systems. The aircraft and its autopilot, however, should not automatically be called independent constituent systems because the autopilot normally lacks the operational and managerial independence associated with formal system-of-systems definitions (Maier, 1998).

Flight data as an analytical trace of system behaviour

Routine flight-data monitoring provides a time-ordered record of selected aircraft states, configuration changes, automation modes and control-system outputs. Such data may include altitude, airspeed, vertical rate, heading, pitch, roll, engine variables, autopilot engagement, selected targets, flap and landing-gear commands, flight-control positions and touchdown or braking parameters.

These parameters provide evidence about system behaviour, but they are not themselves functions. A parameter may indicate the state, input, output or performance of a function. Several parameters may be required to interpret one function, and one parameter may contribute evidence to several functions.

For example, radio altitude, vertical rate, pitch, flight-path angle and air–ground logic may together provide evidence about the flare and touchdown transition. Autopilot status, selected speed and flight-control response may together provide evidence about automation management. Flap-handle position records a cockpit selection, but it does not by itself explain who selected it, why it was selected or whether the resulting configuration was achieved as intended. Flight data is therefore a quantitative trace across the interfaces of the aircraft, automation and pilot-control systems. It may show that a mode changed, a target was selected or the aircraft responded, but it does not necessarily capture intention, diagnosis, workload, ATC communication, visual conditions or the reasoning behind an intervention. Flight-data analysis should distinguish recorded state from inferred function and known evidence from reconstructed context.

FRAM as a candidate methodology for such an analysis

FRAM provides a means of transforming flight data from a collection of separate signals into evidence about interacting system functions (i.e. an IFSM). Recorded parameters can be associated with functions such as establishing landing context, providing air-data observations, managing aircraft configuration, maintaining the vertical profile, controlling energy, monitoring stability, managing the transition between automated and manual control, executing the flare and controlling rollout.

This shifts the analysis beyond isolated parameter exceedances. It enables the analyst to ask what conditions were supplied to a function, what output it produced, how that output affected downstream functions and how the interaction contributed to the observed trajectory.

Aircraft-state parameters provide evidence of physical response. Automation-mode data indicates which automated control functions were active. Cockpit selections provide partial evidence about pilot actions. Navigation and wind data describe aspects of the operational environment. ATC instructions, visual cues and crew reasoning may remain absent from the recorded dataset, but the FRAM model preserves the functional locations at which those influences would be expected to enter.

FRAM therefore acts as an interpretive bridge between recorded data and wider system behaviour. It does not convert every measurement directly into a function, nor does it automatically supply missing causal explanations. It provides a structured functional model within which evidence can be located, couplings can be examined and gaps can be made explicit.

From interpretive models to executable representations

The development described here should not be characterised as the replacement of "soft" models by superior "hard" ones. Soft Systems Methodology, organisational cybernetics and related approaches address questions of purpose, perspective, legitimacy and boundary that no amount of mathematical precision can settle automatically. A computationally exact model may still formalise the wrong system, exclude important stakeholders or encode an inappropriate interpretation.

An executable IFSM model should not begin with equations alone. It should begin with an explicit system of interest, a justified boundary, the functions within that boundary, the interfaces with surrounding systems, and the purposes for which the model is being constructed. Only then should the functions be provided with activation conditions, state variables, thresholds, equations, timing rules and data links.

Standard FRAM is primarily a qualitative and semi-formal method for modelling functional interaction and performance variability. Execution requires an additional computational layer (the FMI / FMV software). A data-linked or executable FRAM model may then use recorded values to update metadata, evaluate coupling effectiveness, trigger functions, apply timing rules or replay operational sequences. Such an extension can support simulation and comparison of alternative scenarios, but its assumptions must remain visible and open to challenge.

The IFSM proposition

A related body of work that must be distinguished from the present proposal is Eisenbart et al.'s Integrated Function Modelling framework. (Eisenbart et al., 2017). IFM was developed within engineering design to integrate the different function-modelling perspectives used across disciplines, using interlinked matrix-based views to support interdisciplinary modelling of system functionality. It is therefore conceptually adjacent to Functional Systems Modelling, particularly in recognising that the term function has different meanings in different modelling traditions.

The distinction is one of purpose, scope and ontology. IFM integrates views of function for engineering design. Functional Systems Modelling, as proposed here, uses the function as an active, situated unit of system performance. Its concern is not only how functions may be represented during design, but how interacting functions, boundary interfaces, data, feedback, variability and learning produce behaviour in operating socio-technical systems. In this sense, FSM is complementary to IFM rather than a replacement for it: IFM addresses the integration of function-modelling perspectives; FSM addresses the recursive modelling of functional systems in action.

Interactive Functional Systems Modelling can thus now be defined here more precisely:

"as a recursive modelling perspective in which systems are represented as dynamically bounded organisations of interacting functions. It begins by establishing purposes, perspectives and boundaries; formalises transformations, regulatory roles, couplings and control relationships; links those functions where appropriate to empirical state data; and may progressively develop qualitative models into executable representations of nested and interacting system behaviour".

Its novel, distinctive contribution is not a new diagrammatic notation. It is the integration of several modelling commitments that are usually separated. Soft systems thinking establishes why the system is being modelled and from which perspective. Engineering functional modelling identifies what must occur. Cybernetics describes feedback and regulation. Organisational systems thinking introduces purpose and viability. FRAM represents the interaction and variability of performed functions. Data provide empirical traces of selected states and exchanges. Computational rules may then support replay, exploration and simulation.

The progression from cells to pilots makes this argument understandable. A cell maintains its identity through interacting internal functions and regulated exchanges across its membrane. Cells combine into organs, organs into patients, and patients interact with clinical systems. In aviation, the aircraft, autopilot, pilot function, air traffic system and operational environment form interacting functional systems whose combined behaviour produces the flight.

The biological and aviation systems are not identical, and the analogy should not be pushed beyond its useful limits. What recurs is the analytical pattern: functions interact; interfaces mediate exchange; regulation maintains viable behaviour; lower-level systems participate in higher-level wholes; and observed outcomes arise from organised interaction rather than from isolated components. That recurring pattern is then the foundation of IFSM.

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