SYSTEMS ENGINEERING RESEARCH CENTER

SERC DOCTORAL STUDENT FORUM 2024 | NOVEMBER 13, 2024

Towards A Hetero-functional Graph Theory Approach to MegaProject Management

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What are MegaProjects?

"Ambitious, complex, and transformative—megaprojects are massive, one-of-a-kind investments spanning public and private sectors. With costs often exceeding a billion dollars, years of development, and a profound impact on millions, they redefine the scale of what's possible."

Why MegaPtojects Fail?

- Iron Law of MegaProjects
- Deliberate misrepresentation and dissemination of false information
- The surgery was a success, but the patient died

Presentation Outline

Goal: to argue that MBSE/HFGT can provide an effective means for improving Megaproject Management Performance

- **Introduction: The Limitations of (Formal) Graph Theory & Multi-Layer Networks**
  - *Formal graph theory and multi-layer networks are fundamentally limited by their ontology → Limited applicability to mega-project management.*
- **Introducing the Denicol Paper[1] in the Context of HFGT**
  - *The HFGT Meta-architecture is discussed in the context of Denicol's exposition of mega-projects and their management.*
- **Denicol's Literature Review Results**
  - *Six Themes of Results are recalled and addressed from a HFGT perspective.*
- **Denicol's Literature Review Conclusions**
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Primary Conclusions

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- **Designing the System Architecture → MBSE/HFGT Approach**
  - *Denicol et al. advocate for designing the system architecture of megaproject management. An MBSE-HFGT approach can serve to address this need.*
- **Bridging the Gap w/ Manufacturing → HFGT Approach**
  - *Denicol et al. advocate for bridging the gap with manufacturing. HFGT was developed for mass-customized, highly reconfigurable manufacturing operations and can address this need.*
- **Building & Leading Collaborations → HFGT Approach**
  - *Denicol et al. advocate for building and leading collaborations. HFGT specifically addresses a diversity of collaboration/decision-making structures including centralized, distributed, decentralized, hierarchical, coordinated/uncoordinated.*
- **Engaging Institutions & Communities → HFGT Approach**
  - *Denicol et al. advocate for engaging institutions and communities. This could be an interesting direction to extend HFGT. See NSF GCR project.*
- **Decomposing & Integrating the Supply Chain → HFGT Approach**
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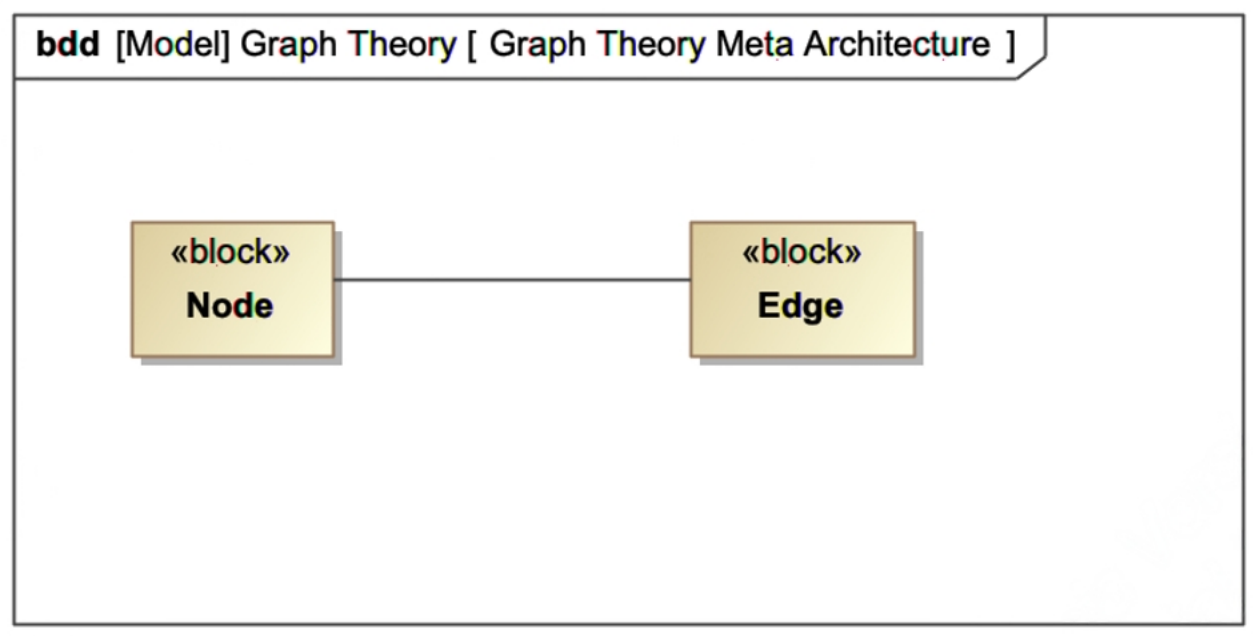
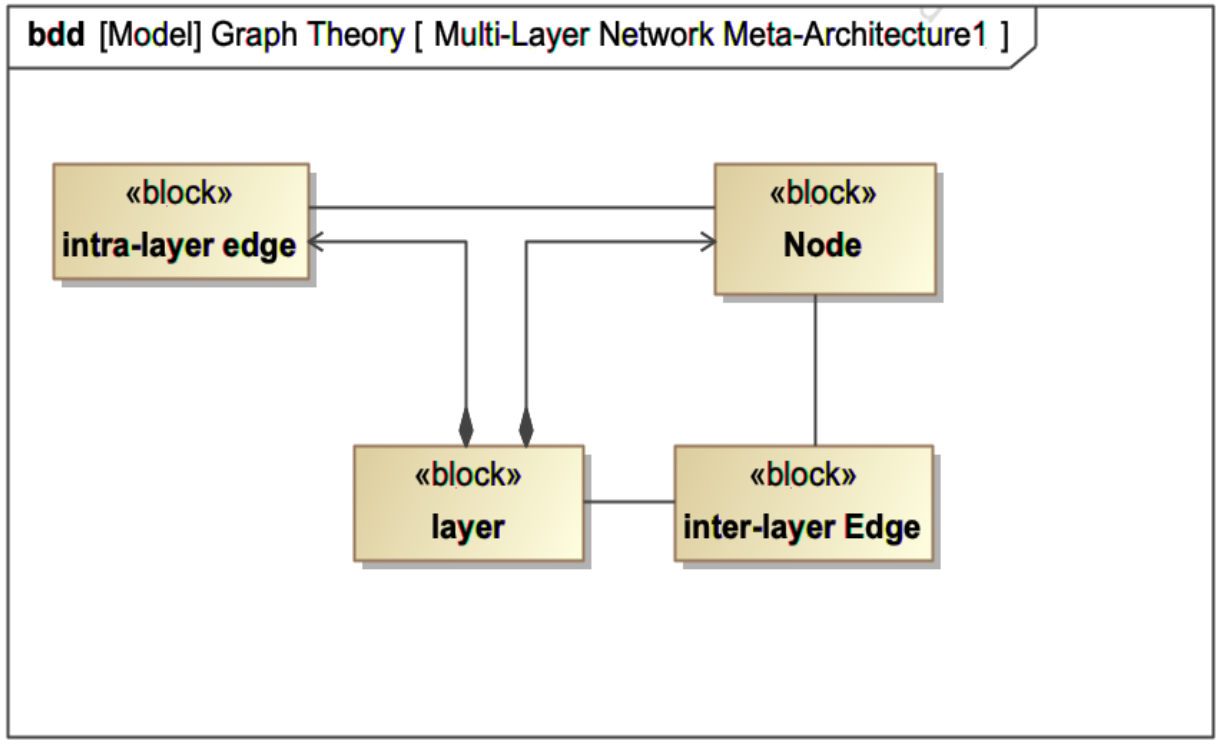
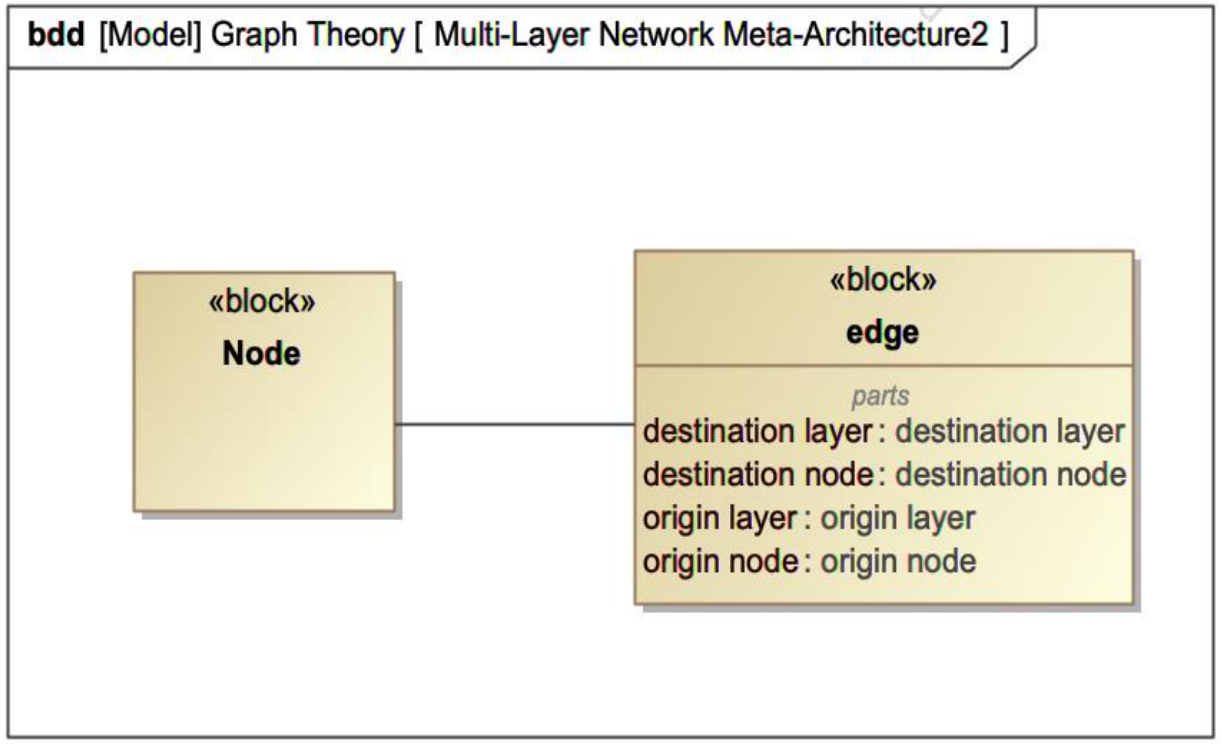
Graph Theory Meta-Architecture



At its core, graph theory represents systems through the interconnected structure of nodes and edges.

Multi-Layer Network Meta-Architecture



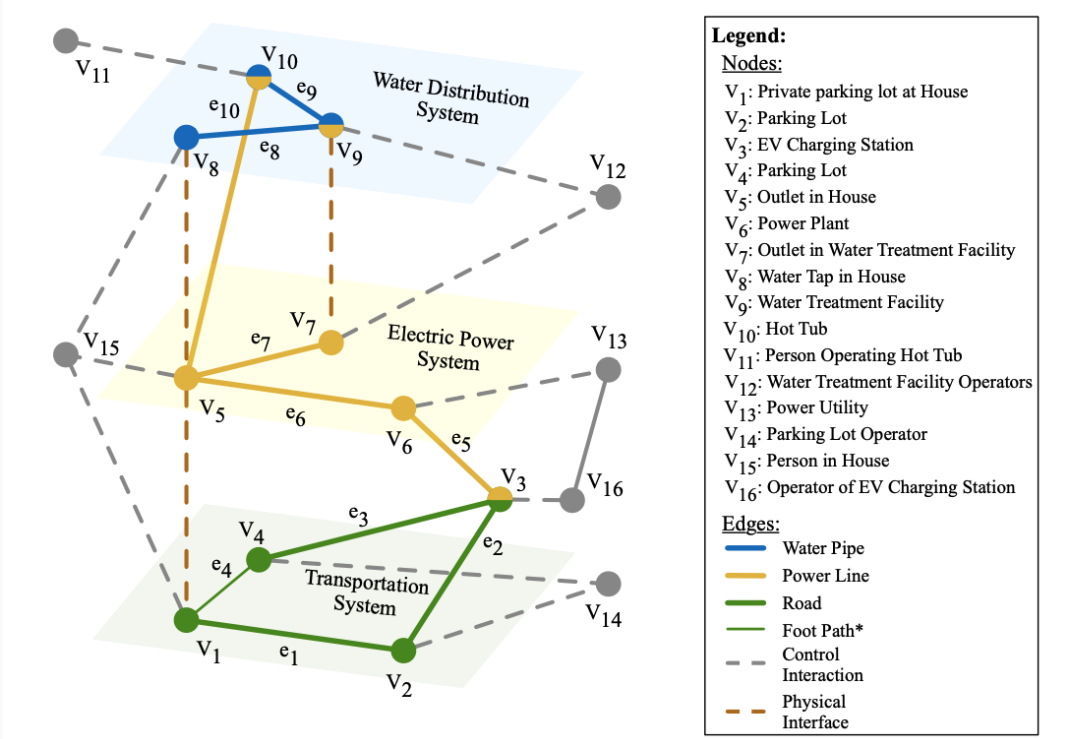


In multi-layer networks, nodes and edges are structured across layers, enabling a richer representation of interdependent and intra-dependent relationships.

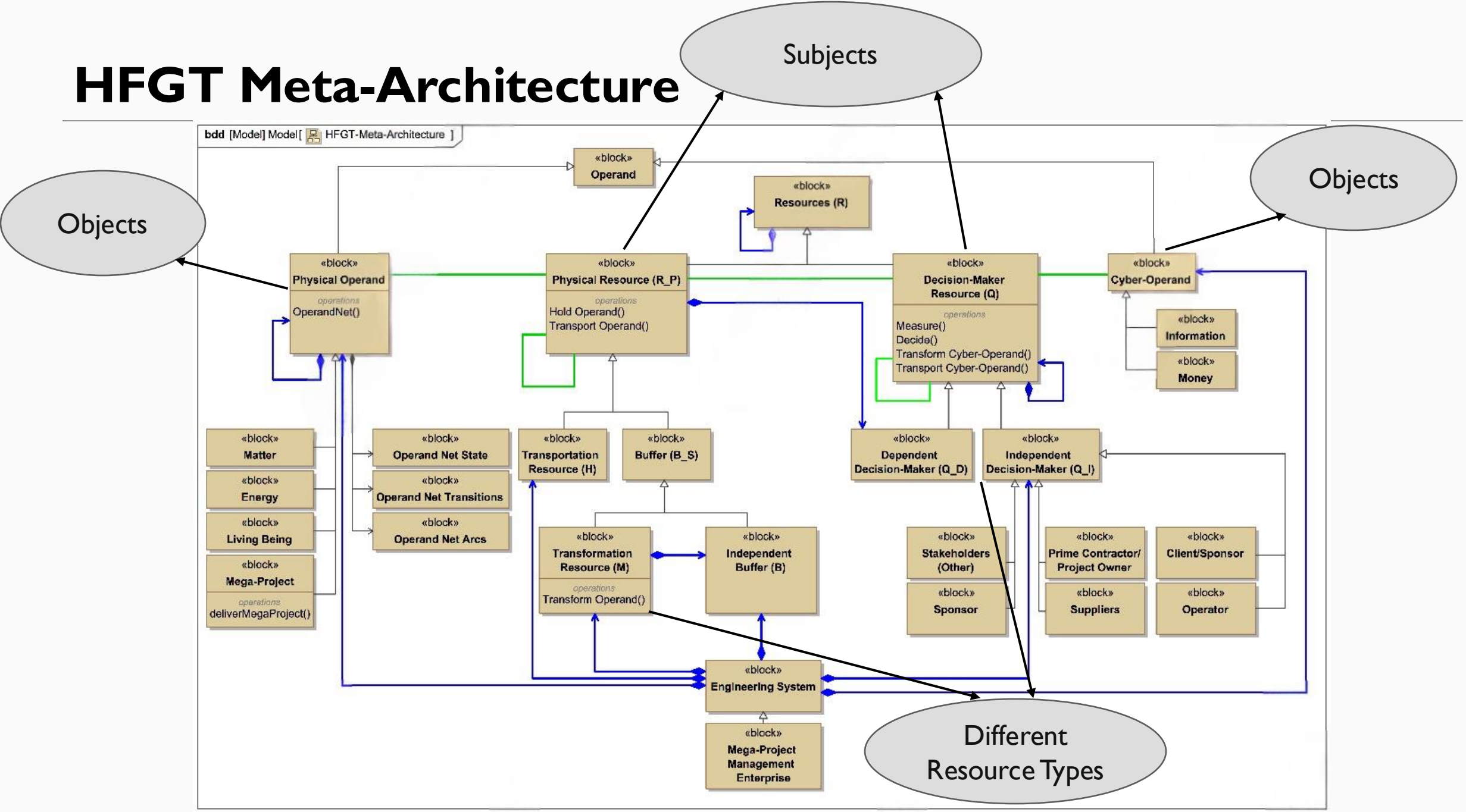
Limitations of Multi-layer Networks

- Many modeling & analytical approaches rely on a graph theoretic framework, but *these frameworks struggle to represent multi-disciplinary systems*.
- Kivela et. al. (2014) have found that ***all*** multi-layer network models adhere to ***at least one*** of the following modeling limitations:
  1. *Alignment of Nodes between layers*
  2. *Disjointment between layers*
  3. *Equal number of nodes for all layers*
  4. *Exclusively vertical couplings between layers*
  5. *Equal couplings between layers*
  6. *Node counterparts are coupled between all layers*
  7. *Limited number of modelled layers*
  8. *Limited number of aspects for each layer*

Despite their flexibility, multi-layer networks face inherent limitations that can restrict their applicability to complex, multi-disciplinary systems.



HFGT Meta-Architecture



HFGT's Potential in Convergence Science

HFGT can model an arbitrary number of heterogeneous networks of arbitrary topology and connect them arbitrarily. (Something multi-layer networks can't do).

- **Natural/Engineering Scientist**: HFGs reconstitute the conservation laws of matter and energy for systems with explicit heterogeneity
- **Decision/Control Scientist**: HFGs support centralized, decentralized, hierarchical, and collaboratively distributed decisions
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HFGT demonstrates high convergence science potential for many disparate fields!

Contribution of HFGT Structural Analysis

The contribution of Hetero-functional Graph Theory

1. HFGT can be applied to interdependent infrastructure systems of arbitrary topology.
2. The theory is extensible in the number of physical elements and functions within the city.
3. HFGT can accommodate as many infrastructure systems as required in the analysis.
4. HFGT is fundamentally about systems with directed graphs.
5. HFGT is fundamentally cyber-physical.
6. ***Ultimately, HFGT posits that there is underlying meta-architecture system architecture that can be applied generically.***

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Introduction

Denicol et al Paper

Established as a standalone temporary organization, megaprojects can be led by a client team, prime contractor, or some form of temporary alliance, joint venture, or coalition of multiple parties (owners, sponsors, clients, contractors, suppliers, and other stakeholders) that work jointly on a shared activity for a limited period of time in an uncertain environment (Jones & Lichtenstein, 2008; Merrow, 2011).

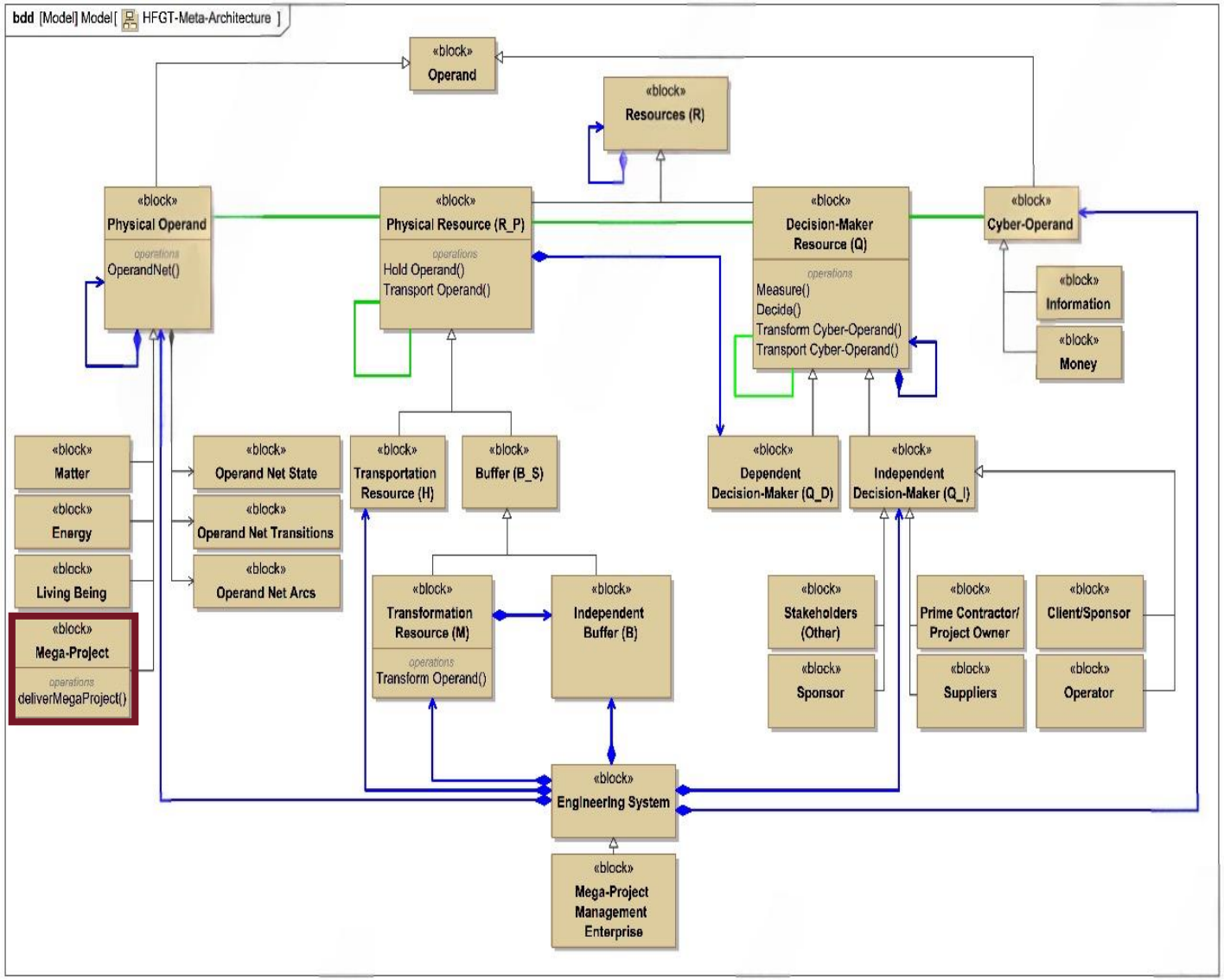
HFGT Response

HFGT uses decision-making resources to model enterprises (i.e. temporary organization) that can be decomposed into

1. Stakeholders (including the client team),
2. Prime contractor (as the primary entity responsible for conducting the project as resources)
3. Temporary alliance (which is just a collection of contractors with peer-to-peer relationships)
4. Joint ventures (see #3)
5. Coalition of multiple parties (See #3)

HFGT treats the "mega-project" as the operand of the enterprise that must be delivered. Mega-projects – as a type of operand – has :

1. Uncertain state
2. Uncertain context outside system boundary



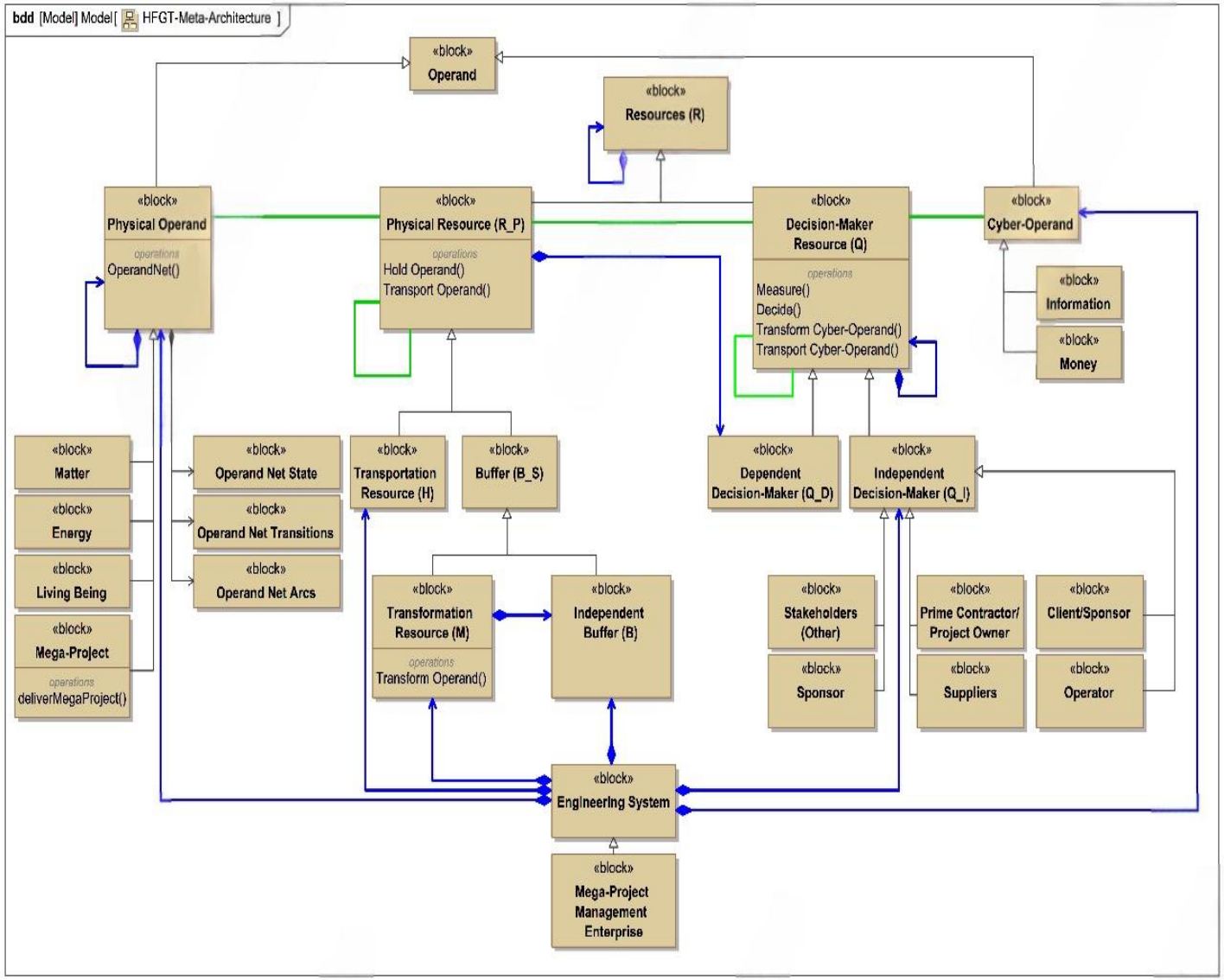
Introduction

Denicol et al Paper

Each megaproject is usually decomposed into many smaller inter-related projects and organized as a program.

HFGT Response

HFGT treats the "mega-project" as the operand of the enterprise. These operands can be decomposed as necessary to described smaller projects.



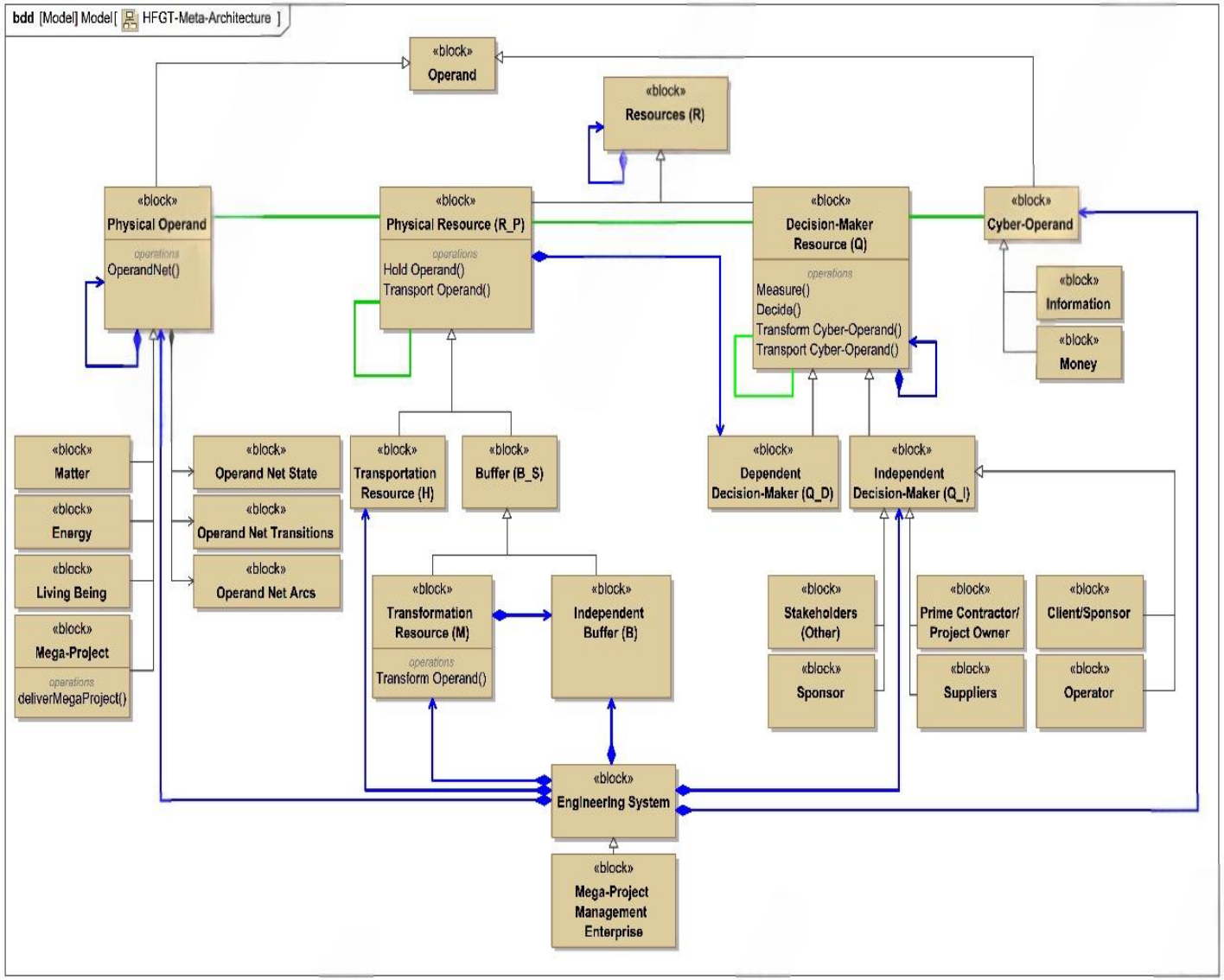
Introduction

Denicol et al Paper

We found that each concept draws upon its own distinct theoretical foundations and frameworks, although there is no space in this article to explore each in detail.

HFGT Response

By representing mega-projects explicitly as a classification of the HFGT meta-architecture, we hypothesize that HFGT can provide a unifying theoretical foundation and framework for synthesizing and analyzing mega-projects and their management.



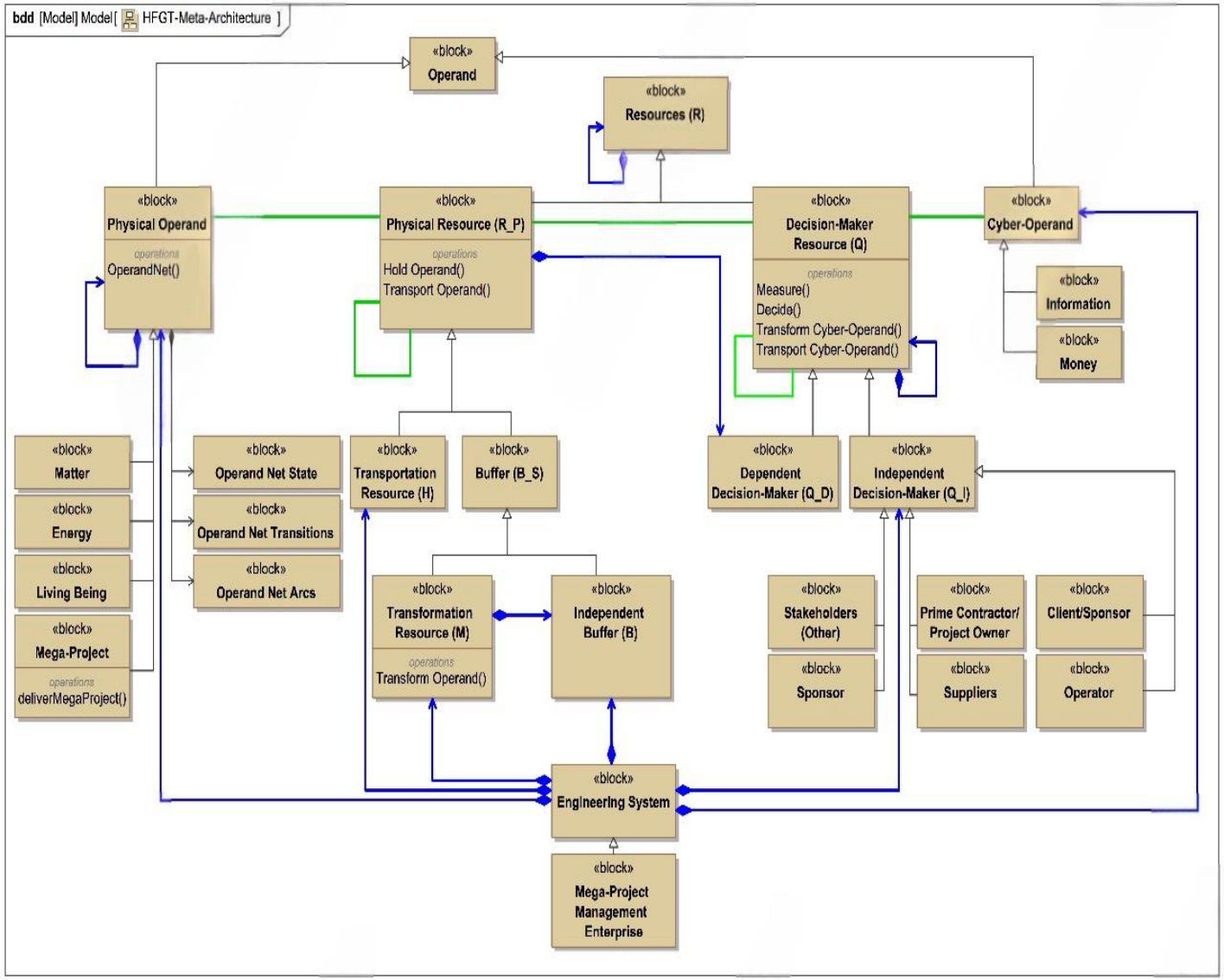
Introduction

Denicol et al Paper

While significant efforts have been made to improve our understanding of megaproject performance, each contribution alone provides insights into a partial or isolated phenomenon. There is no overarching theory or framework that can connect the disparate contributions into a complete picture identifying how performance depends on various components such as decision making, integration, leadership, and teamwork—working together as an integrated whole.

HFGT Response

By representing mega-projects explicitly as a classification of the HFGT meta-architecture, we hypothesize that HFGT can provide a unifying theoretical foundation and framework for synthesizing and analyzing mega-projects and their management. Decisions executed by decision-making resources are explicitly treated. The integration of projects into mega-projects is captured by the associated (blue) decomposition arrow and (green) association link. While leadership, in the socio-psychological sense, is not currently treated via HFGT, the structure of decision-makers in peer and hierarchical structure is treated via the (green) association link.



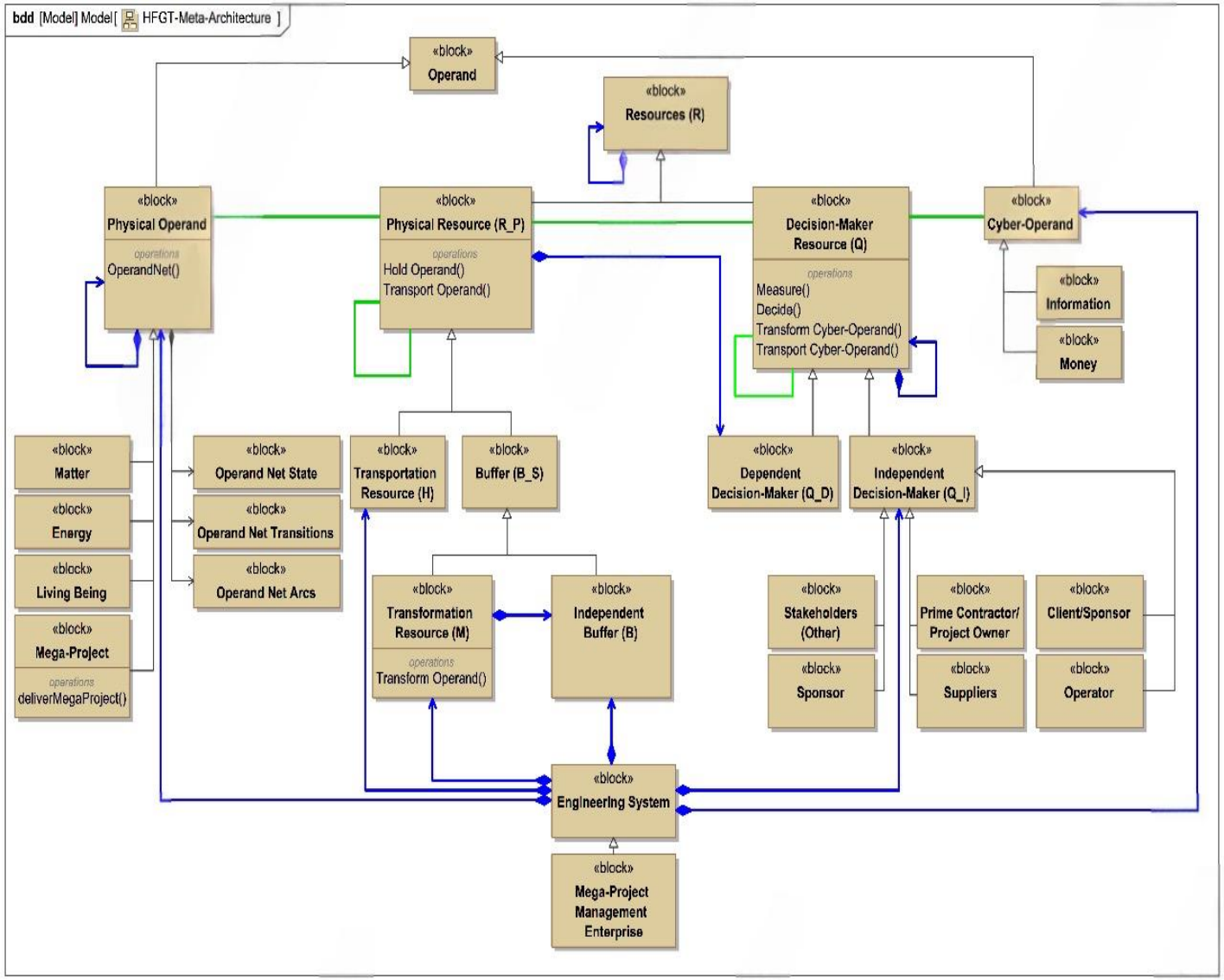
Introduction

Denicol et al Paper

We conclude the article by suggesting that new research and theory building should adopt a systemic view, taking into account some of the different aspects impacting megaproject performance. We suggest the literature could be enhanced by research that considers a megaproject as a system of production and by studying their individual topics through a systems lens.

HFGT Response

By representing mega-projects explicitly as a classification of the HFGT meta-architecture, we hypothesize that HFGT can provide a unifying theoretical foundation and framework for synthesizing and analyzing mega-projects and their management. Early work on HFGT was tailored to mass-customized production systems, their architecture, and their performance. Therefore, HFGT is consistent with the recommendation above.



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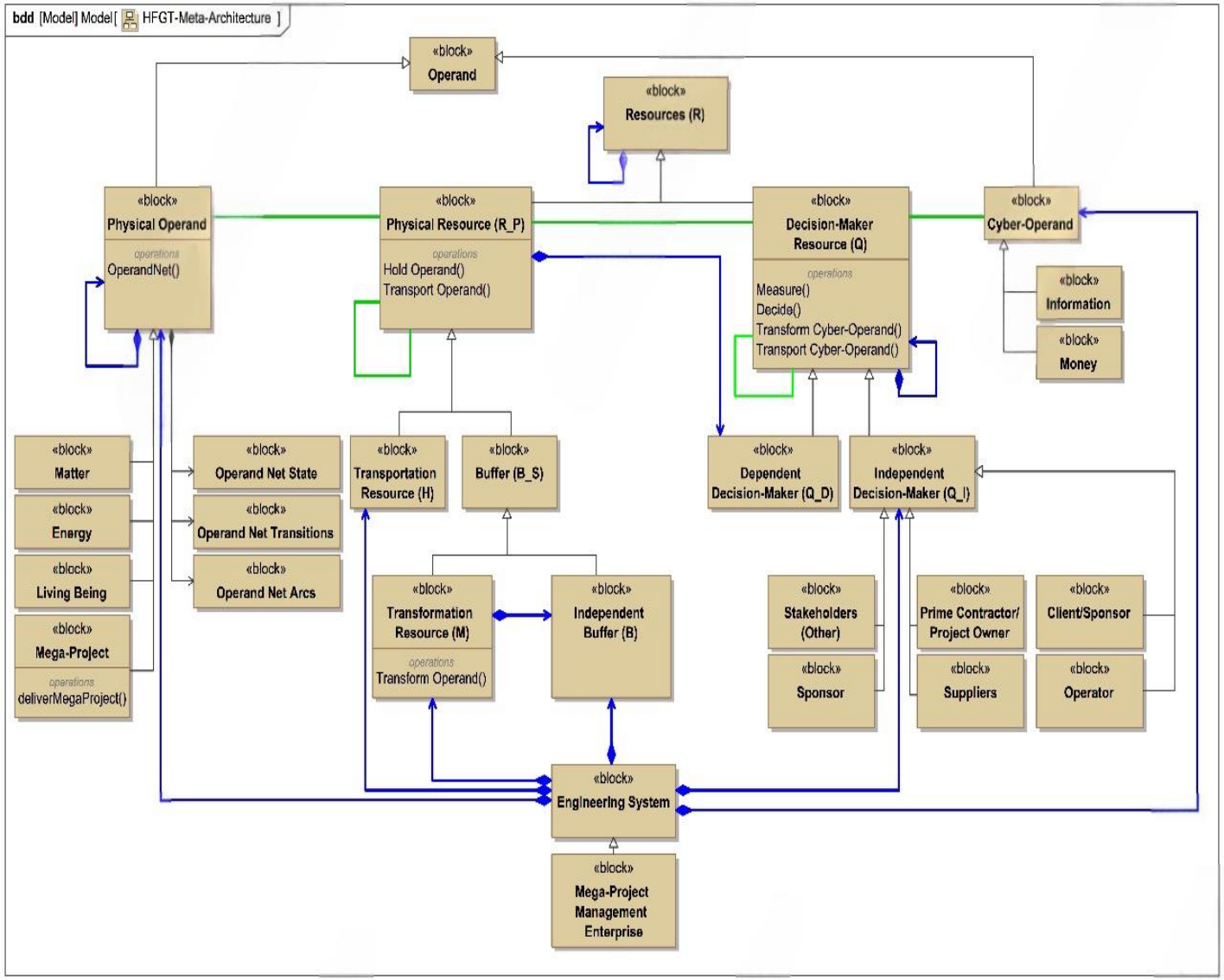
Results

Denicol et al Paper

After executing the analysis as outlined in the Methods section, the literature dataset of 86 articles were clustered into six themes: (1) decision-making behavior; (2) strategy, governance, and procurement; (3) risk and uncertainty; (4) leadership and capable teams; (5) stakeholder engagement and management; and (6) supply chain integration and coordination.

HFGT Response

1. HFGT treats decision-making behavior a serial and parallel arrangement of decision processes. It also models decision-making resources and allocated decision-making processes to them.
2. HFGT treats strategic processes/decisions as a type of decision-making behavior. Same goes for governance decisions and procurement decisions.
3. HFGT treats risk/uncertainty as stochastic quantities in the states of the megaproject system or in the flows entering the megaproject system. HFGT directly supports stochastic discrete event system simulation via stochastic/fuzzy Petri nets.
4. HFGT treats leadership as a type of "decision-maker" and "capable teams" as a "physical resources" capable of carrying out various processes in the megaproject enterprise.
5. HFGT treats stakeholders as a type of decision-maker (even if they only have the ability to hard/soft influence). The management of stakeholders appears as the adjacency/communication between various types of decision-makers.
6. HFGT has addressed a wide diversity of continuous/streaming and discretized supply chains.



Theme I: Decision-Making Behavior

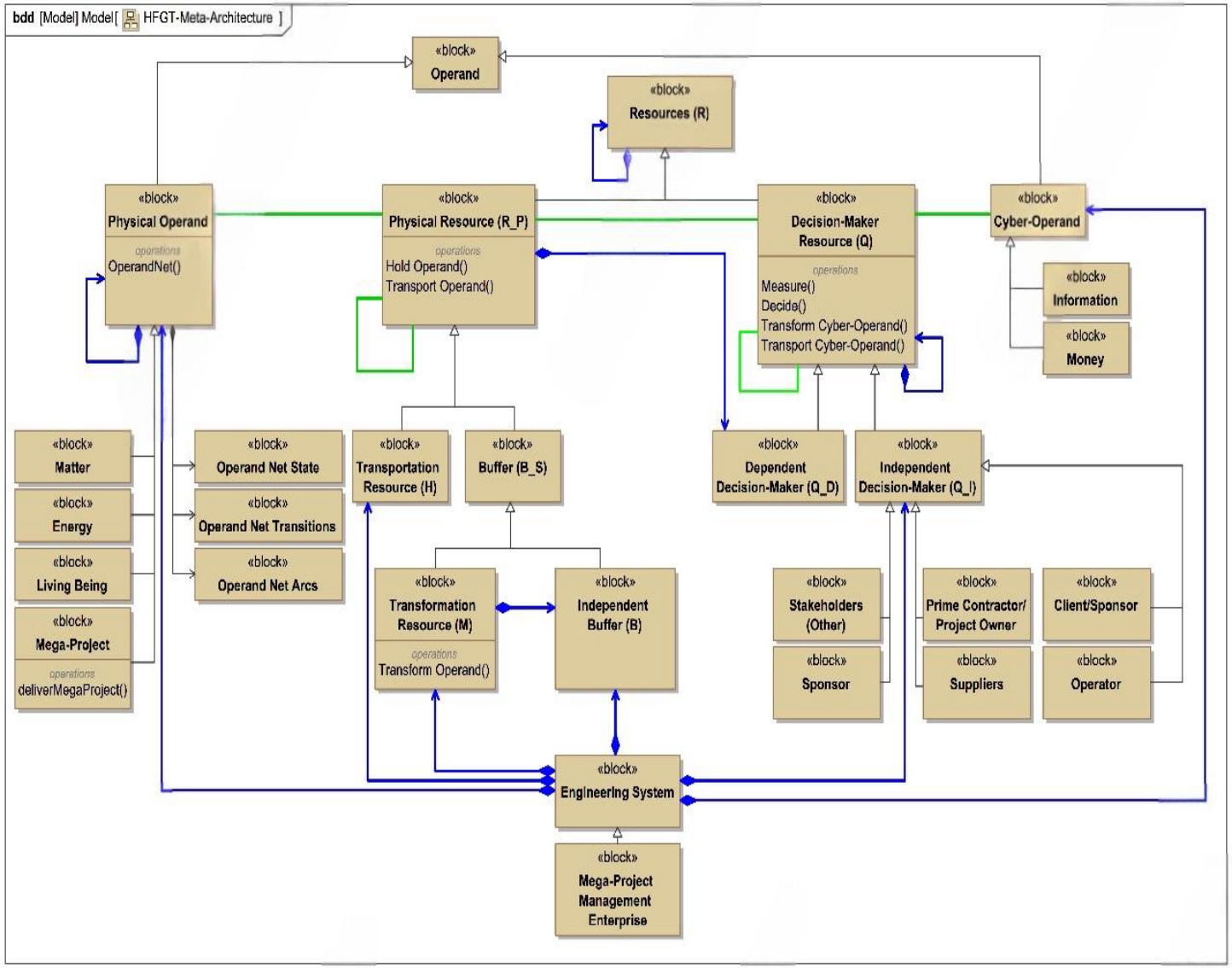
Denicol et al Paper

The three most predominant concepts in this theme are:

1. optimism bias (delusion): executives are overly optimistic and thus overestimate benefits and underestimate costs;
2. Strategic misrepresentation (deception): executives strategically misrepresent the truth and seek to satisfy their own interests; and
3. Escalating commitment: executives continue to follow the pattern of behavior leading to unsuccessful outcomes rather than follow an alternative course of action.

HFGT Response

1. Optimism bias can be addressed potentially in two ways. 1.) The use of a HFGT stochastic discrete-event simulation model can serve to provide a more realistic picture of project execution so as to bring project managers back to reality 2.) The decision-making processes can be simulated so as to explicitly include optimism bias into the the simulation.
2. Socio-cultural problem: A model is only as good as the data you feed it. So this is more difficult to address. It is impossible apply machine learning to determine the veracity of the data being put into the model as a "meta" capability. See work "The spread of true and false news online".
3. Socio-cultural problem: The use of a HFGT stochastic discrete-event simulation model can serve to enhance rational rather than irrational decision-making. Ultimately, the absence of rational models invites the potential for irrational decision-making founded in ill-conceived mental models.



Theme II: Strategy, Governance, and Procurement

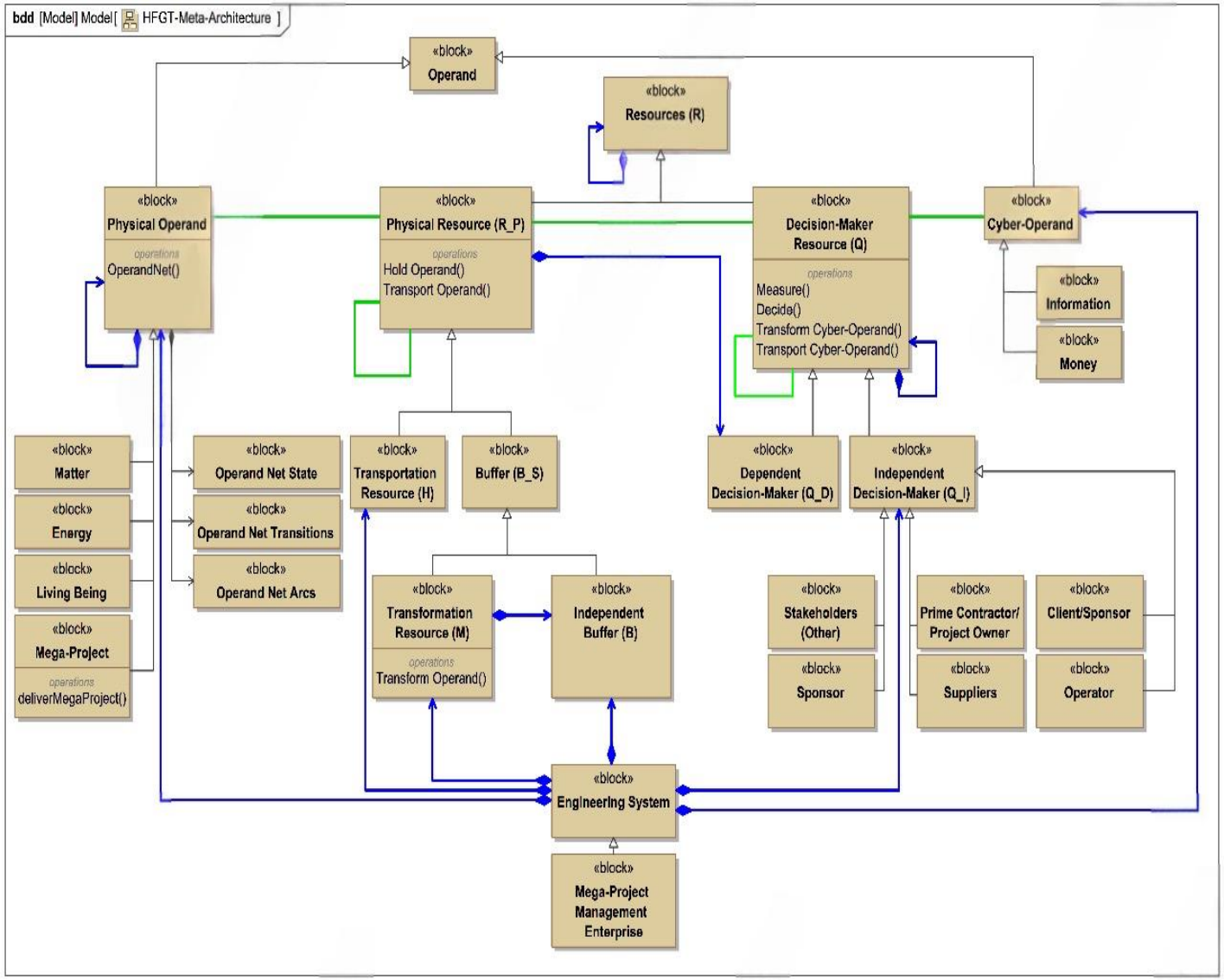
Denicol et al Paper

The three most predominant concepts in this theme are:

1. Sponsor, client, owner, operator: associated with the roles and responsibilities of these entities throughout the project life cycle, with particular emphasis on the front-end stage;
2. Governance: linked to the delegation of authority formally and informally, at the organizational and individual levels; and
3. Delivery model strategy: related to the strategy adopted by firms to organize themselves in combination with partners and suppliers, and combining in-house and external capabilities to best organize and deliver the project.

HFGT Response

1. HFGT highlights the roles and responsibilities of various stakeholders be they "resources" or "decision-makers" of various types.
2. Same as #1. Ultimately, any modeling and simulation approach based upon theory imposes a formalization of authority (rather than leaving informal approaches)
3. HFGT can describe full supply chain outside of the organization and state the associated peer-to-peer relationships.



Theme III: Risk & Uncertainty

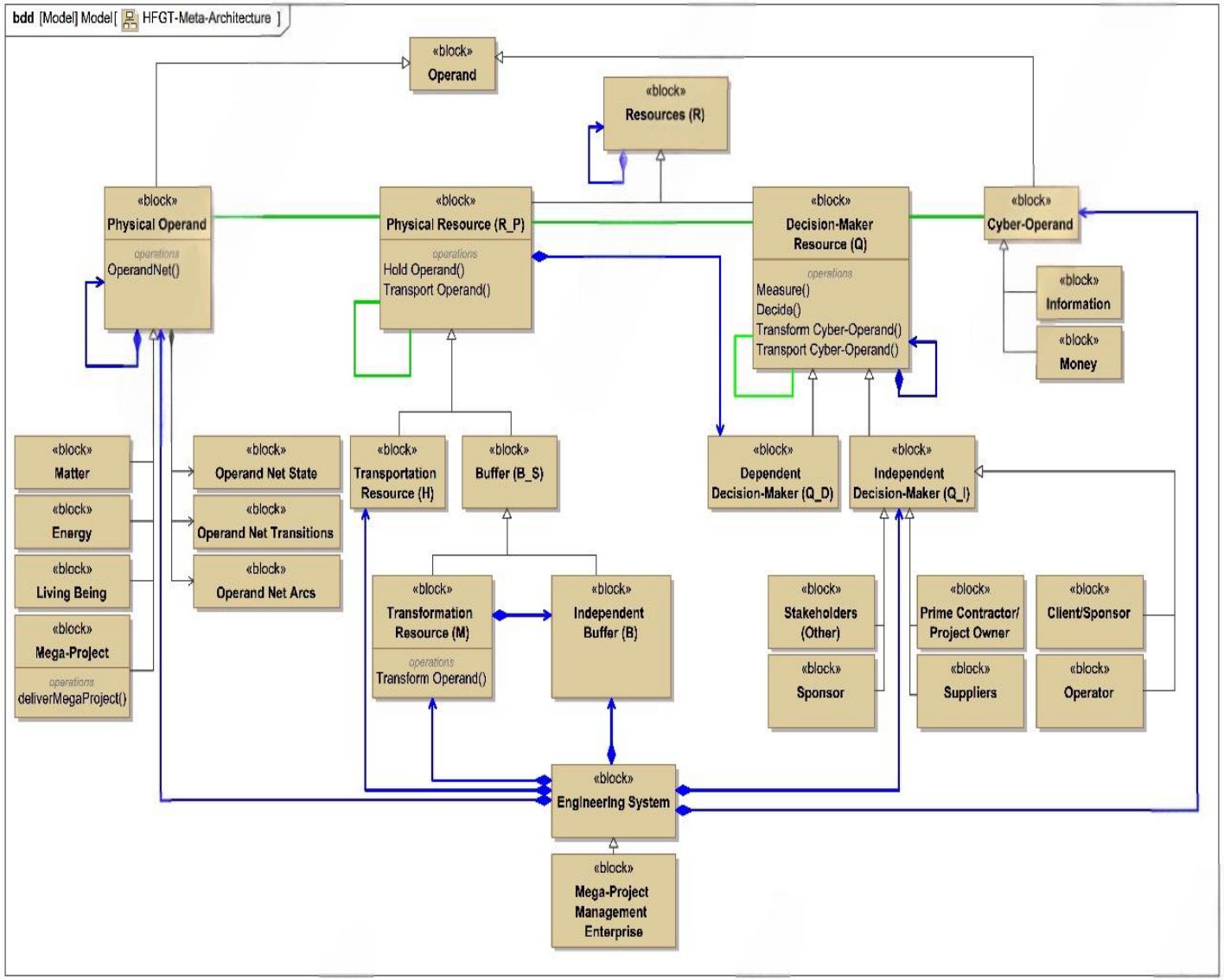
Denicol et al Paper

The three most predominant concepts are:

1. Technological Novelty: first-of-a-kind technologies have frequently being introduced in large innovative projects and are associated with risks;
2. Flexibility: the ability to be adaptive and responsive to changing and uncertain circumstances; and
3. Complexity: the underlying factor of megaprojects that can be defined by the large number of parts and its relationships among each other and with the external environment.

HFGT Response

1. HFGT can handle design challenges with "known-unknowns" because the parametric model of the designed system is known. HFGT is ill-equipped to handle design challenges with "unknown-unknowns" or systems where the synthesis process has yet to happen. You can analyze well what does not yet exist!
2. HFGT explicitly models different types of system flexibility (e.g. flexible manufacturing systems)
3. HFGT explicitly models complexity in system form, system function, and system concept.



Theme IV: Leadership & Capable Teams

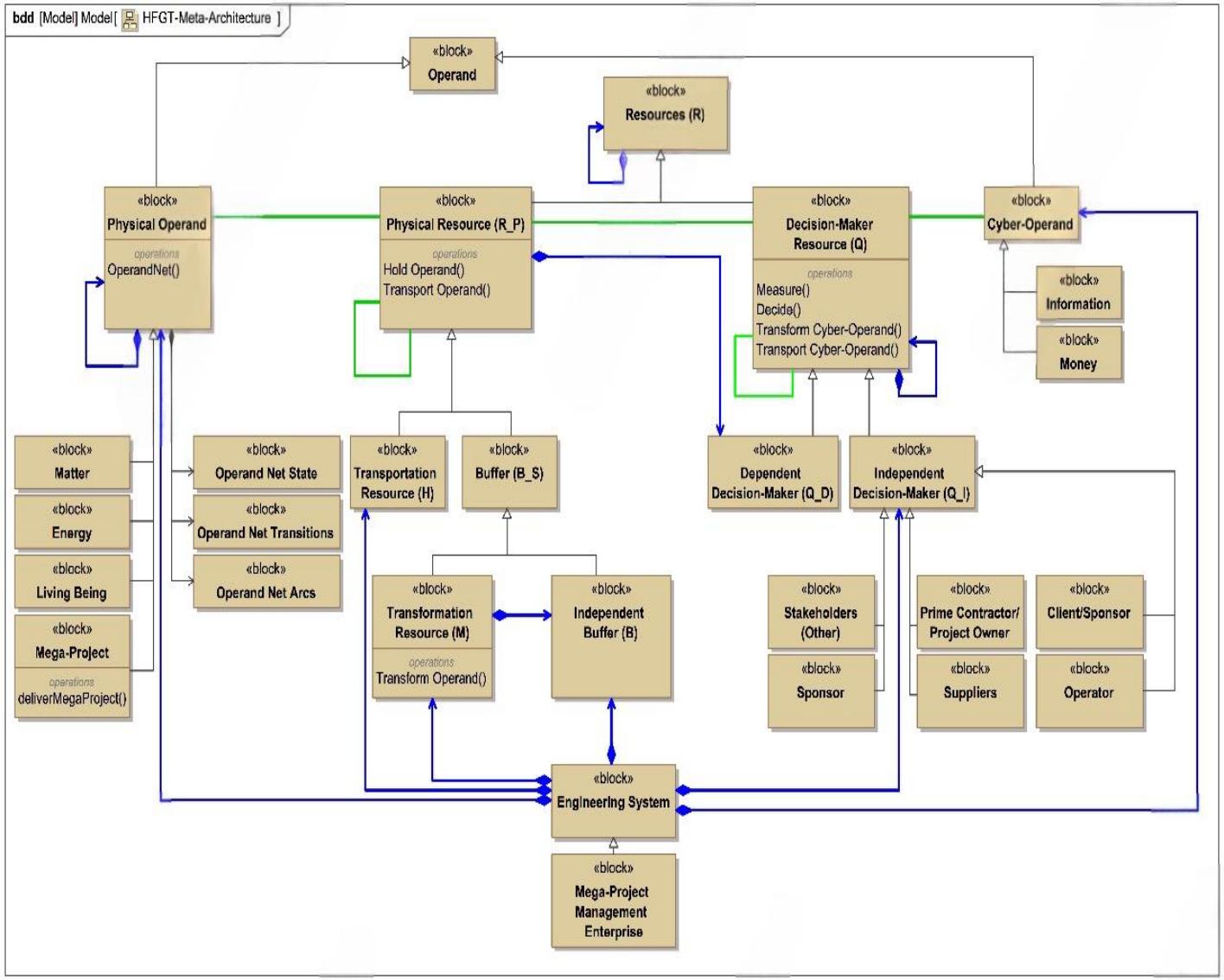
Denicol et al Paper

The three most predominant concepts are:

1. Project leadership: the need for project champions, dedicated leaders who are committed to the success of the project;
2. Competencies: competencies and skills that individuals forming project teams need to possess; and
3. Capabilities: the ability that firms have to produce specific products or services relying upon collective organizational knowledge.

HFGT Response

1. While HFGT cannot easily model socio-cultural notions of leadership, it can model the champions and leaders and the formal roles that they play within an organization.
2. HFGT specifically includes capabilities/competencies of individuals
3. Individual capabilities can functionally aggregate to create organizational competencies.



Theme V: Stakeholder Engagement & Management

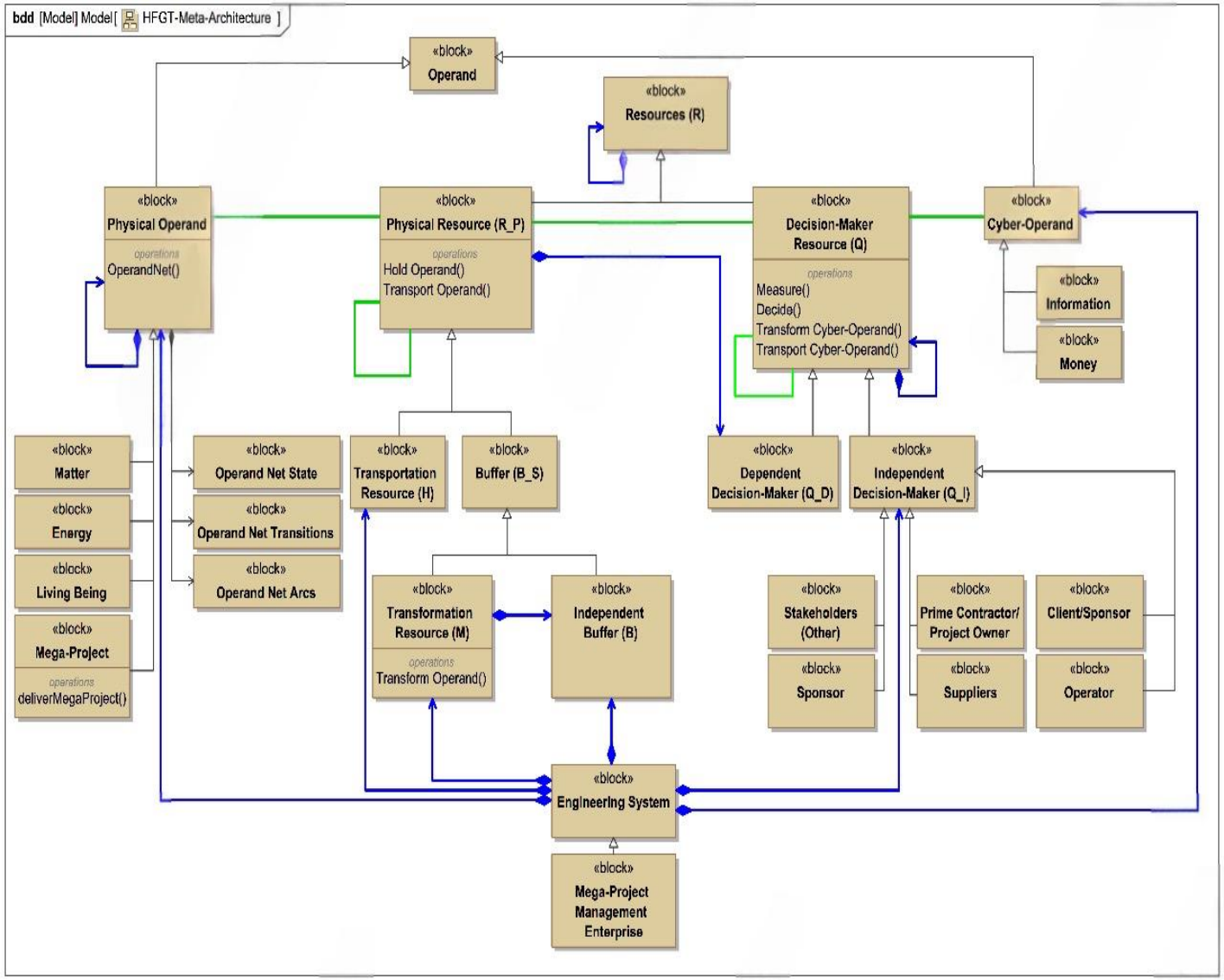
Denicol et al Paper

The three main concepts are:

1. Institutional context: the set of formal organizational structures, rules, and informal norms;
2. Stakeholder fragmentation: the number of parties, which often results in an intense level of interaction among involved stakeholders; and
3. Community engagement: the processes and engagement activities by which the project involves the local population in the project.

HFGT Response

1. HFGT can handle formal organization structures & rules. Informal norms less so.
2. Either model the fragmentation, or use MBSE-HFGT for participatory modeling and engagement.
3. See #2.



Theme VI: Supply Chain Integration and Coordination

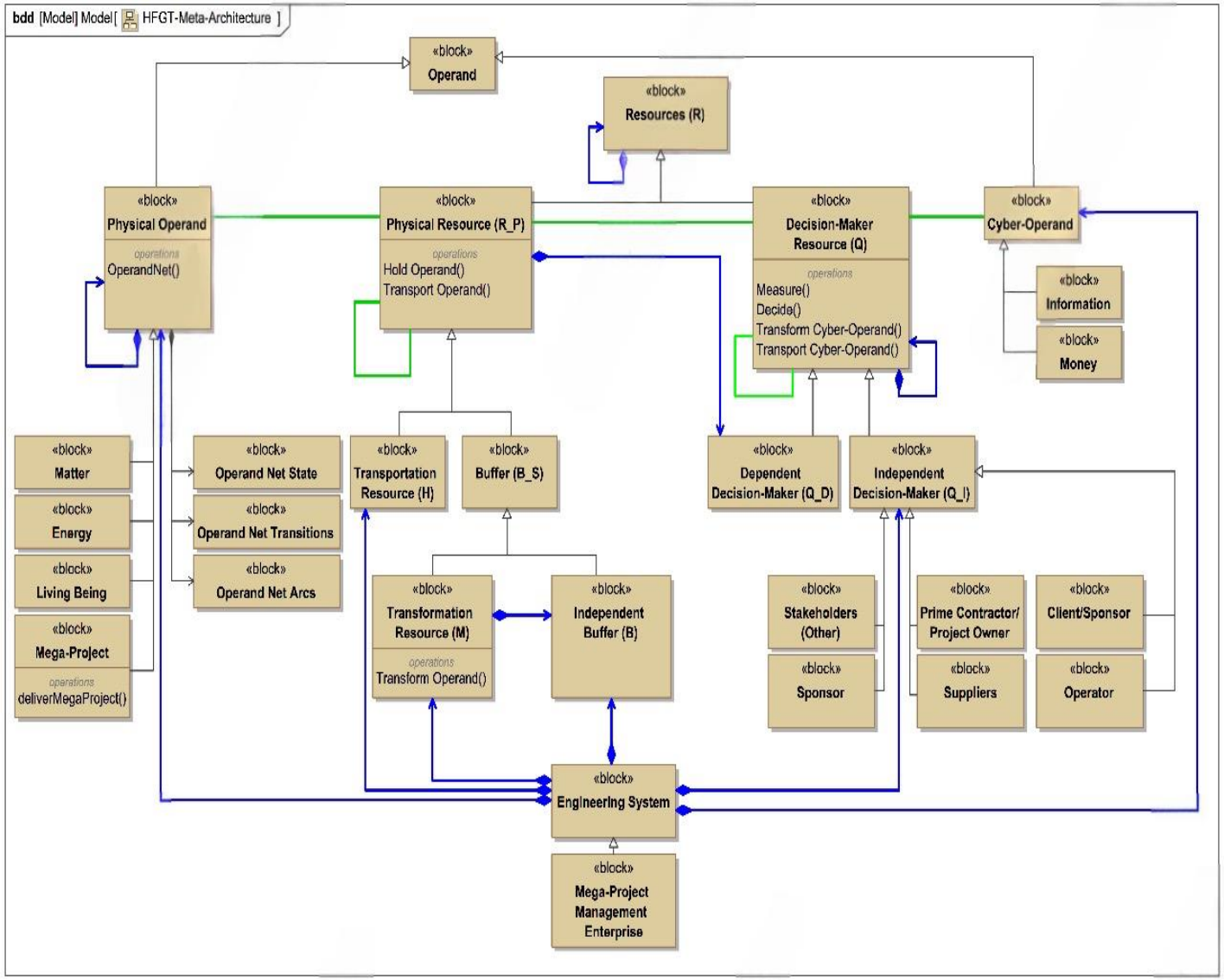
Denicol et al Paper

The three main concepts in this theme are:

1. Program management: associated with systems, procedures, and tools to monitor, control, consolidate, optimize, and achieve benefits from a number of individual inter-related projects;
2. Commercial relationships: linked to the establishment of formal relationships with the organizations delivering projects and subprojects, as well as the management of those interfaces throughout several phases of the project; and
3. Systems integration: related to the technical and managerial capabilities required to integrate several components produced by different parties in order to deliver an operational asset to the client. This integration happens at the system level as intermediary products (projects and subprojects) and at the system of systems level as final products (programs and portfolios).

HFGT Response

1. HFGT can model these straightforwardly as a mega-project composed of multiple projects being executed by physical resources and managed by decision-maker resources.
2. See #1
3. See #1.



Conclusion

Denicol et al Paper

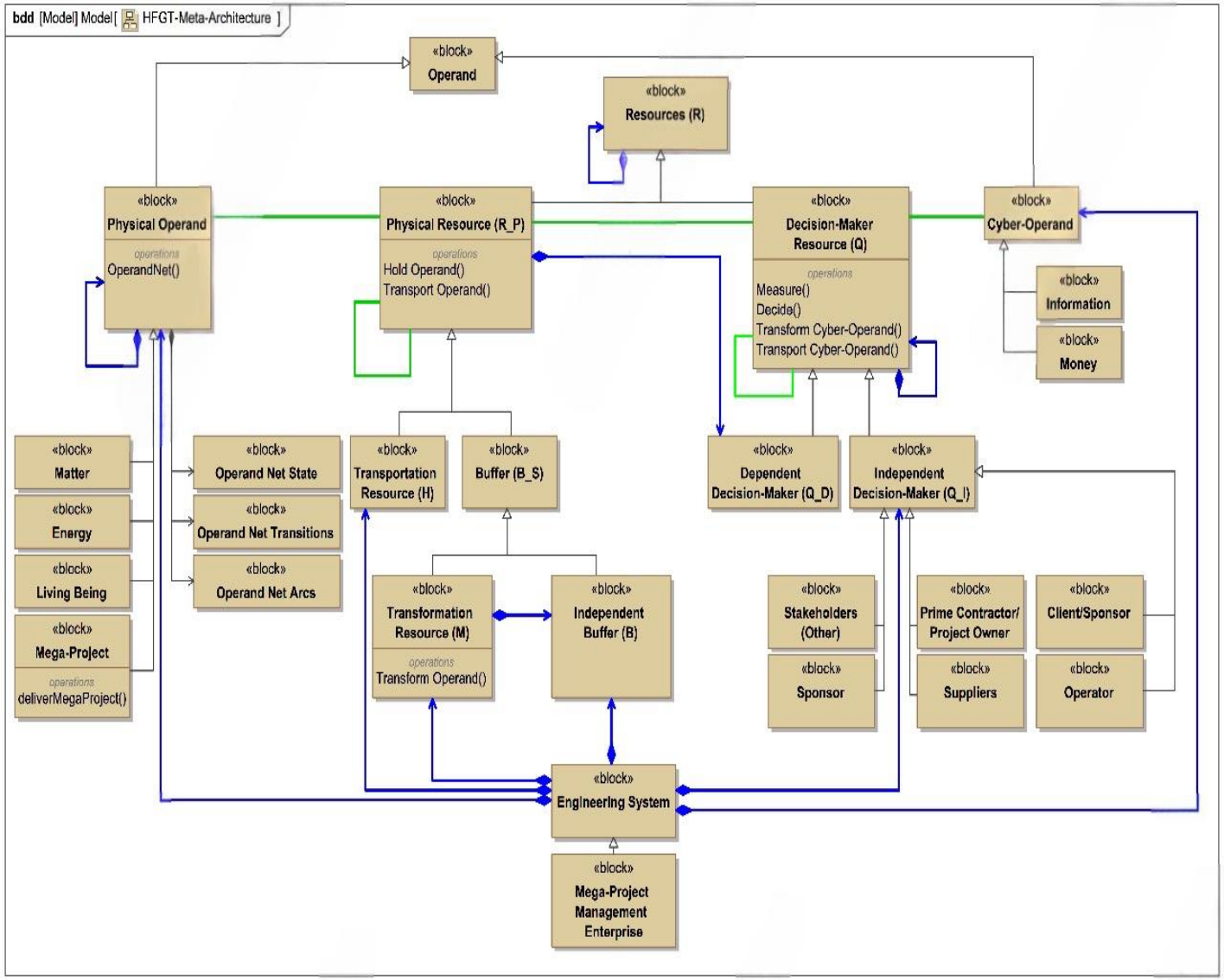
What is missing in current research is an understanding of megaprojects as a complete production system—from planning, through design, manufacturing, and construction, to integration and handover to operations.

The consideration of their interdependencies may inform discussions on how megaprojects could be more comprehensively studied to improve our understanding of topics, such as the (co)creation of value, its evolution, extent, organizational boundaries, and transferability across the ecosystem (Jacobides et al., 2018).

HFGT Response

This is exactly what HFGT is proposing to do. First by modeling via MBSE, then translating into the mathematical equivalent as a hetero-functional graph that can be simulated as a stochastic discrete event system simulation.

Although this may seem difficult, HFGT provides a means of constructing the HFG automatically from closed form formula.



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Thank you!

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