A Systems Engineering Approach to the Incorporation of New Technologies and Innovations in Modular System Upgrades

Romulo Broas, ***PhD Candidate***
Dinesh Verma, ***Doctoral Advisor***

8th Annual SERC Doctoral Students Forum
HOSTED VIRTUALLY ON: November 17, 2020
www.sercuarc.org

Agenda

I. Introduction to Modularity

II. Literature Survey

III. Motivation and Research Statement

IV. Applying Systems Thinking to Modular System Upgrades

V. Optimization Applied to a Modular System: A Preliminary Model

VI. The Optimization Strategy

VII. The m_c Value

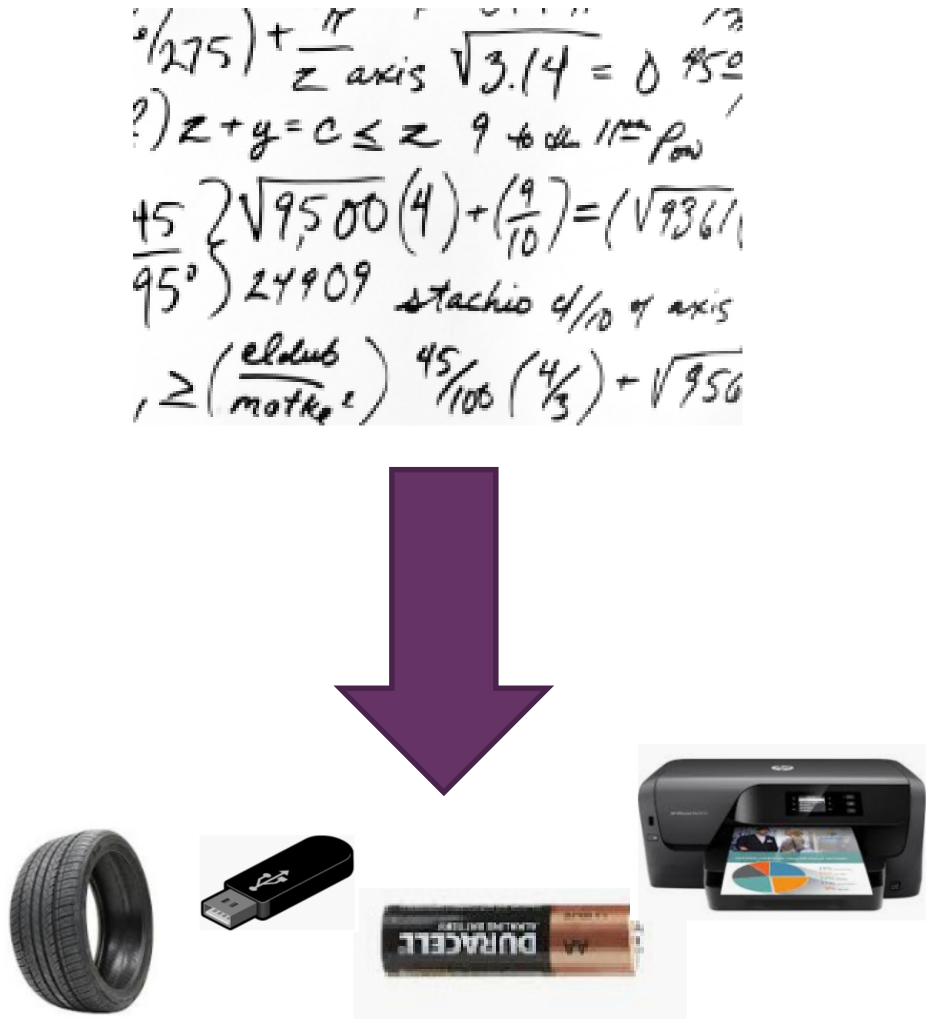
VIII. Conclusion

I. Modularity: An Introduction

- Modularity has been part of human complex reasoning
  - Modularize by breaking down complicated concepts and structures into smaller parts
  - Use smaller concepts and structures as building blocks ("modules") to combine and build larger and more complicated things
  - Formal definitions found extensively in literature
- Modern applications
  - Means to achieve mass production
  - Build and understand complex systems
  - Integrate robustness into designs

II. Literature Survey

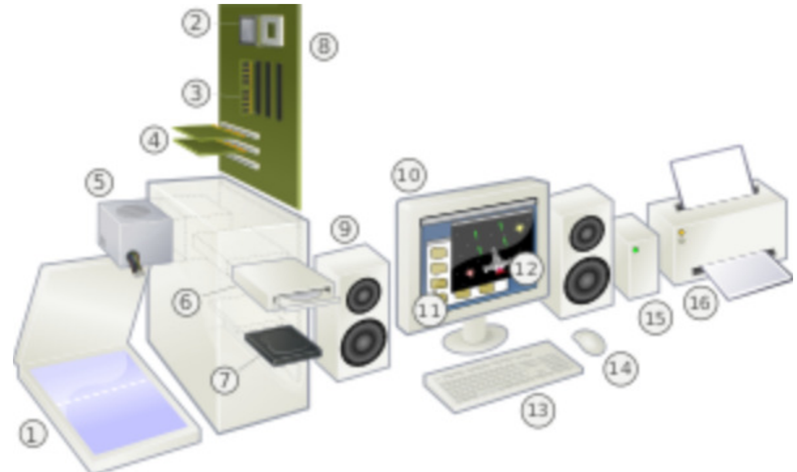
- Mathematical Theory
- Application to Theoretical Systems
- Application to Practical Systems
- Very Modular Systems
- Arguments Against Modularity
- When to Upgrade
- Role of New Technology



Application to Practical Systems

- Modularity is not a binary attribute
  - There are degrees of modularity that is determined by the coupling between components
- Automobiles: perfect example of gradations in modularity
  - One extreme: "Integrated" car has almost no modularity
    - Unique system requirement such as performance (speed, ruggedness, impenetrability, etc) necessitated a custom integration of the car with distinctive parts
    - Very few of these integrated cars produced and they were very expensive
  - Other extreme: "Modular" car has parts modularized to increase commonality
    - Mass produced and cheap
  - In between: most cars exhibited both integration and modularization to varying degrees
    - Had parts that shared commonality with other cars, but other parts of the car were customized to create a unique car
- Example: China built two hospitals in 2 weeks (Jan 2020)

Very Modular Systems

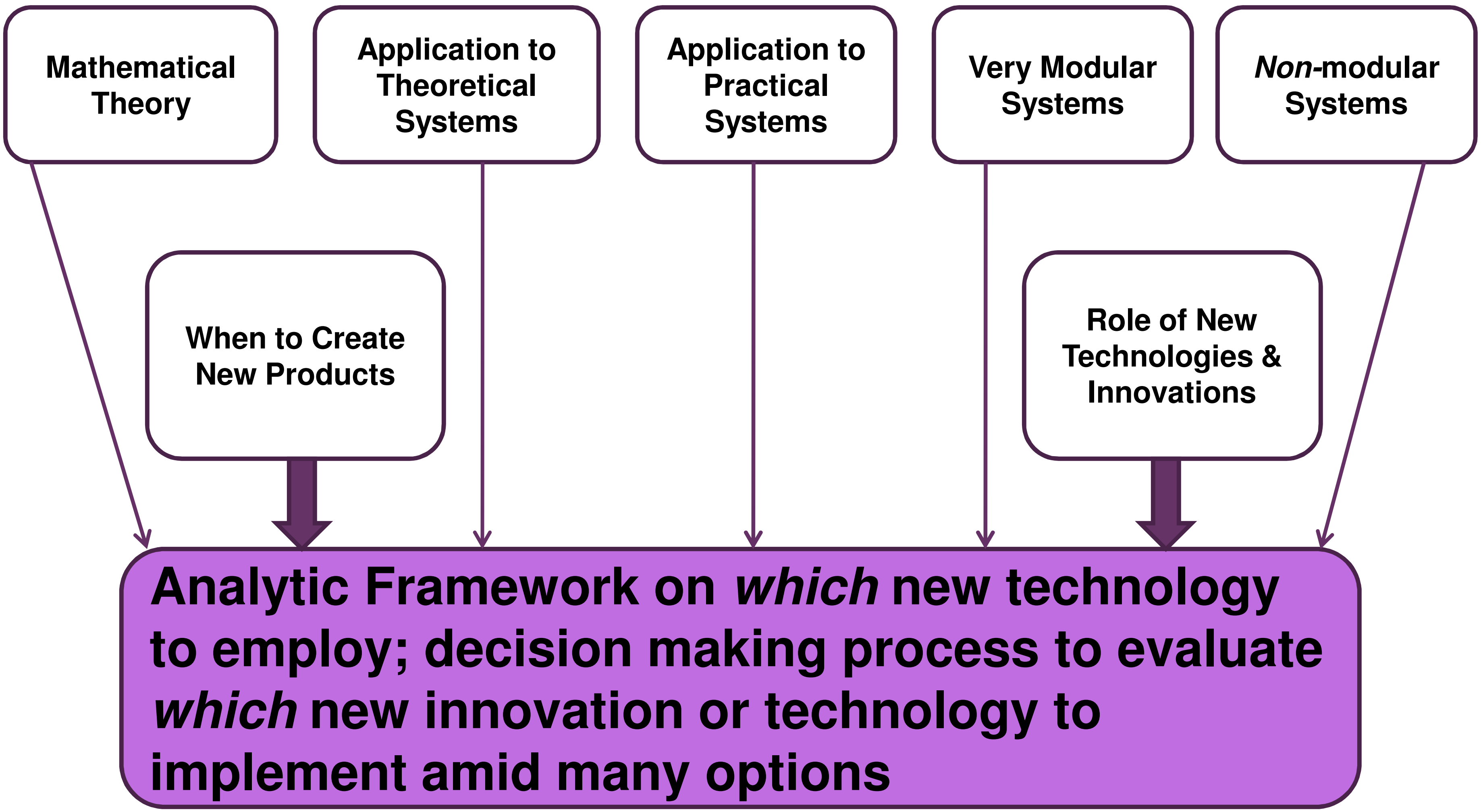


- Legos
- IBM PC
  - Standard ports and interfaces (USB)
  - Plug and play: processors, memory, and various cards can be swapped or exchanged to upgrade and customize a PC
  - In particular, it is the USB port where scanners, webcams, phones, printers, and a plethora of other modules can be added or disconnected that has made PCs a truly modular system

Literature Survey Summary

- Modularity is "a continuum describing the degree to which a system's components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the rules of the system architecture enable or prohibit the mixing and matching of components." (Vasawade, 2015)
- Literature survey on modularity is exhaustive
  - Mathematical theory, application to theoretical and practical systems, modularity in practice, non-modular systems
  - When to create new products
  - Role of new technologies and innovations
- **Broas research** = given a choice of many innovations and technologies, which one should be chosen in a modular system?
  - Consider a company doing research and development to improve a particular module in a system
  - An innovation has been made
  - Should the company integrate the new technology and upgrade the module, or should the company wait for further progress?
  - What are the optimal conditions to pursue upgrades to a modular part?

Literature Survey to Doctoral Research



III. Motivation and Research Statement

The Research

- Modular systems are upgraded through the incorporation of new technologies or innovations
- It is a complex process that involves many stakeholders with varying interests
- The systems thinking concepts of stakeholder, shaping forces, conceptigan, and systemigram analyses are used
- Optimization techniques are explored to see what is the best way to upgrade
- Goal is to better understand the underlying processes, transformations, and relationships that drive the decision to upgrade a module within a modular system

IV. Applying Systems Thinking to Modular System Upgrades

Upgrading Modular Systems

- How can new technologies or innovations be incorporated into modular system upgrades?
- A systems thinking approach can better understand the complexity of upgrading modular systems through the incorporation of new technologies or innovations
- Systems thinking concepts of stakeholder, shaping forces, conceptigan, and systemigram analyses are employed to identify the critical factors involved in a modular system upgrade
- The central role of the Systems Engineer in balancing various stakeholder interests is presented.

Stakeholders

- The stakeholders are key individuals who are affected, impacted, interested, or involved in some fashion with the upgrade of a modular system
- When upgrading a modular system by the incorporation of new technologies or innovations, the active stakeholders are:
  - Systems Engineer
  - Program Manager
  - Innovator
  - Company
  - Customer
  - Competitors

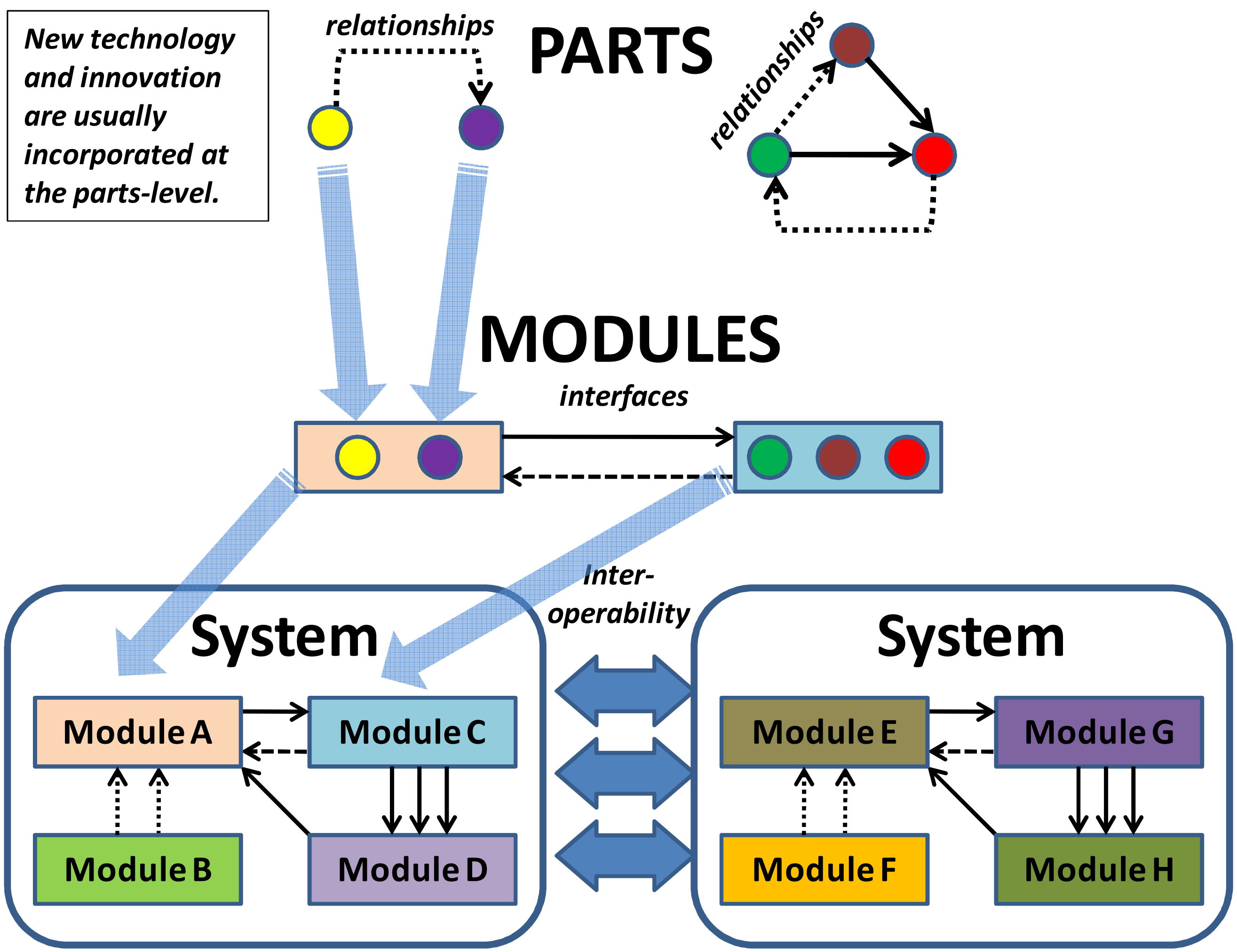
Shaping Forces

- Shaping forces are over-arching themes that have systemically created and molded modular systems throughout time
- In a modular system, a dominant shaping force is its modular design
- Other shaping forces are the new technologies or innovations that will be incorporated into the modules that make up the system

Conceptigan Analysis

- Conceptigan analysis is the application of systems thinking to understand complexity
- Five conceptigan analysis concepts are explored to understand the intricacies of a modular system upgrade and the interplay between various stakeholders when upgrades happen

Hierarchy, Openness, Emergence

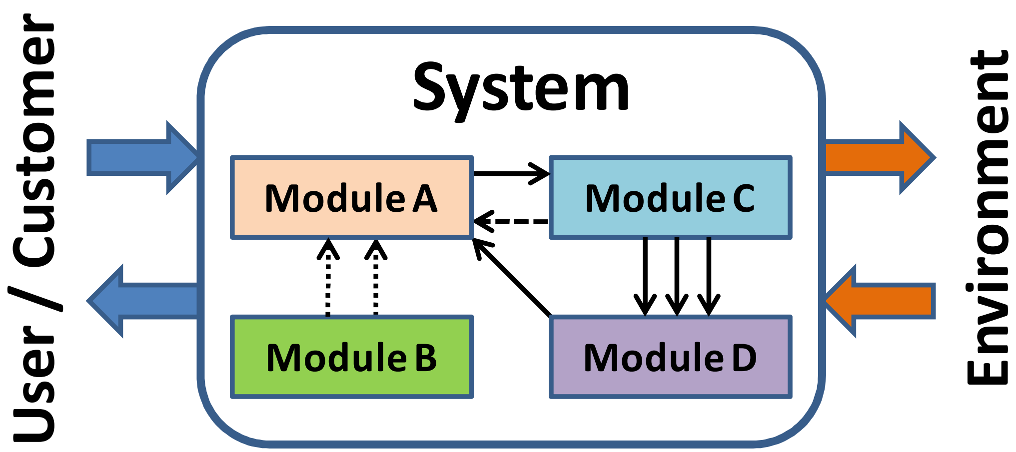


Parts **are related to each other to become modules.**

Modules **are connected by interfaces to become a system.**

Systems **have inter-operability to become a System of Systems.**

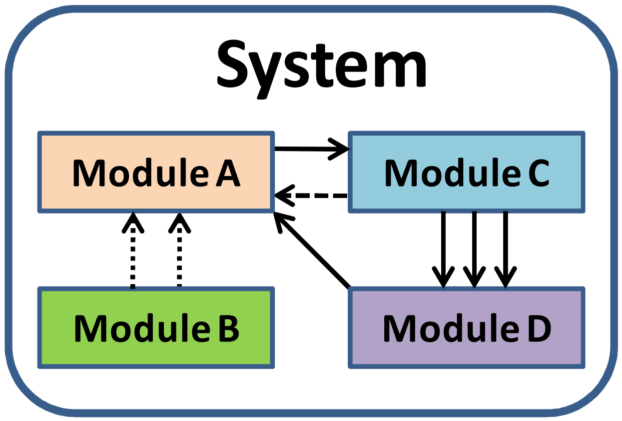
Boundary, Interior, Exterior



There are different levels of boundaries

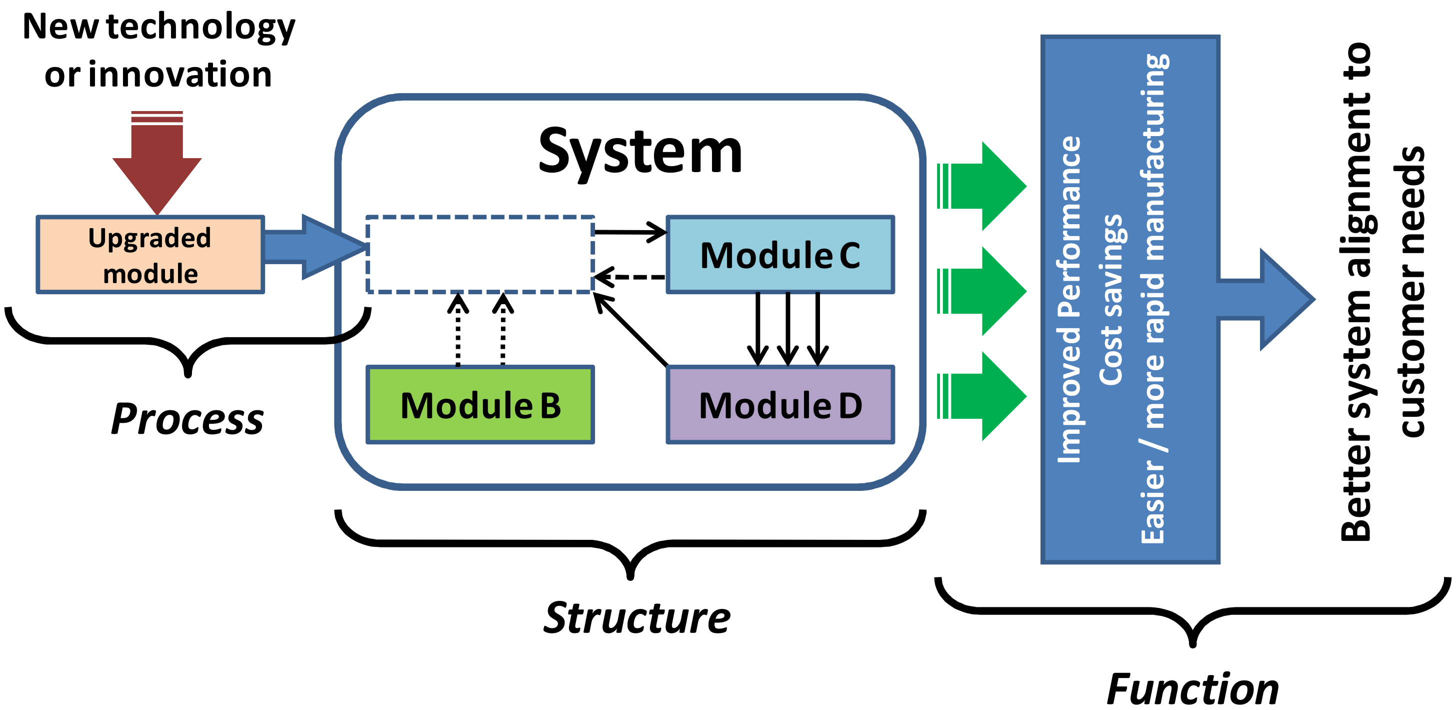
- **Boundaries between modules (connected by interfaces)**
- **Boundary between the user / customer and system**
- **Boundary between the system and its environment**

Wholes, Parts, Relationships



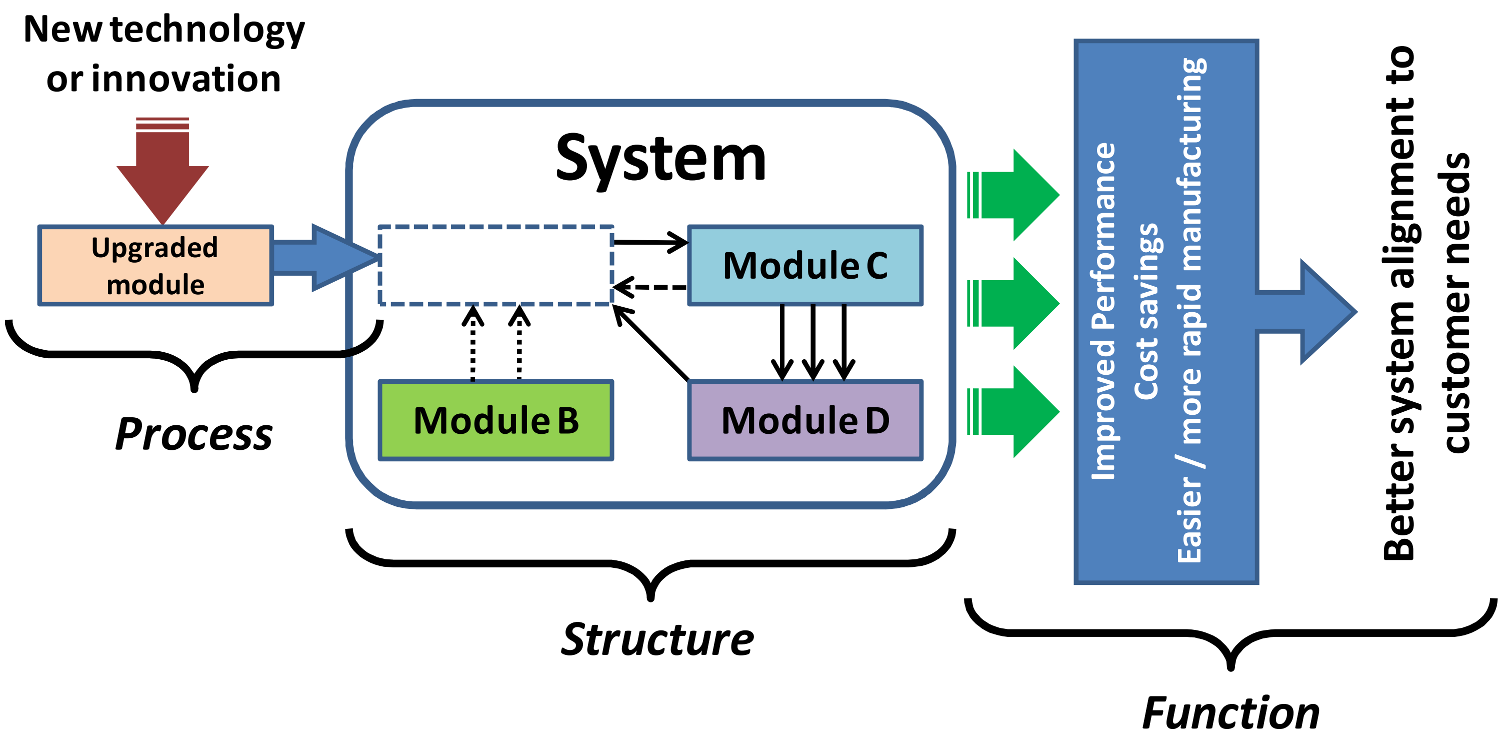
- The Whole is the System
- The Parts are the different modules making up the system
- The relationships between the parts (modules) are the interfaces

Inputs, Outputs, Transformations



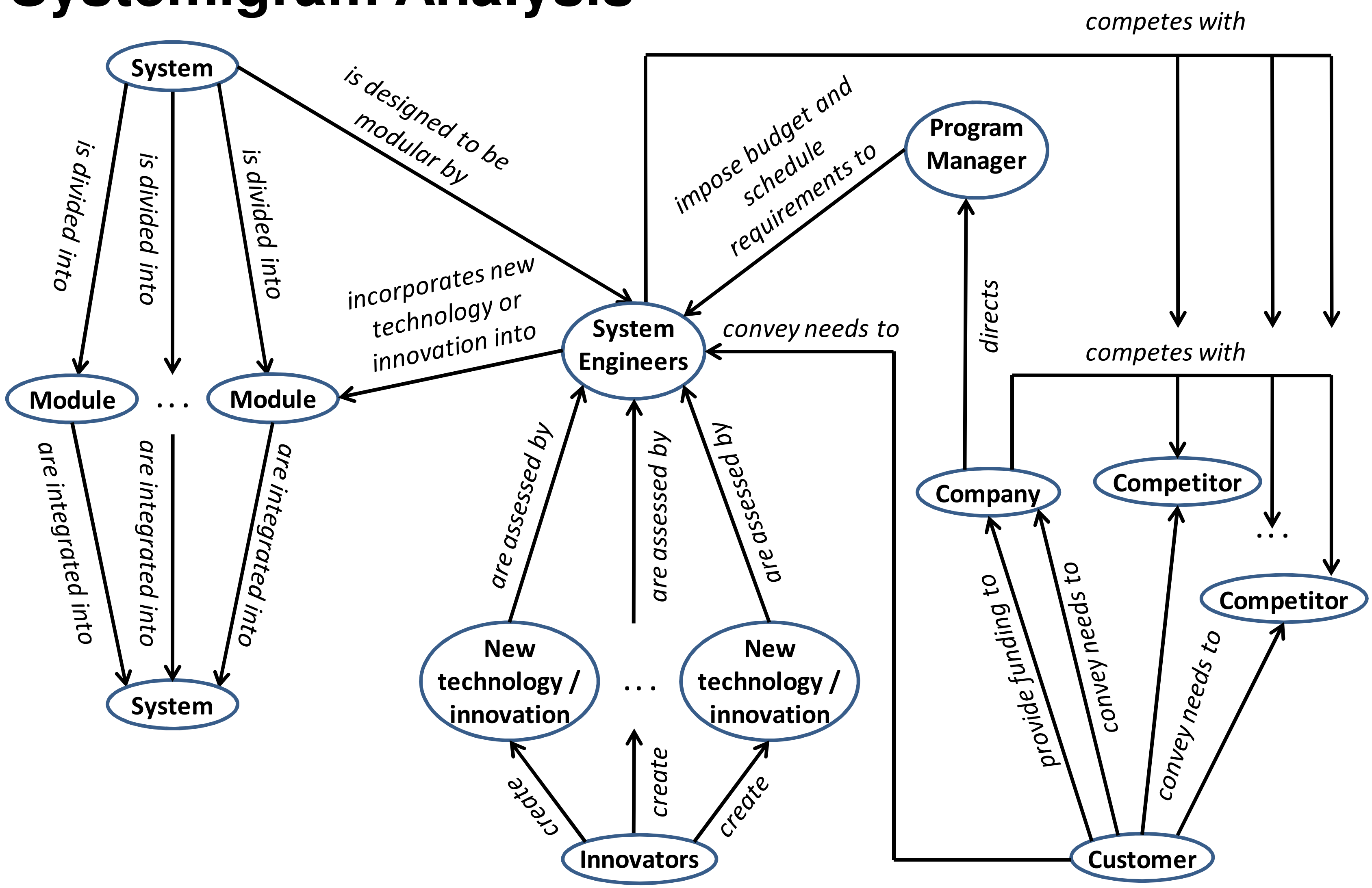
- The **input** is an upgraded module, which was made possible by new technologies or innovations
- The **output** is better system alignment to customer needs
- The **transformations** happening because of the module upgrade could be improved performance, cost savings, *and / or* easier or more rapid manufacturing

Process, Structure, Function

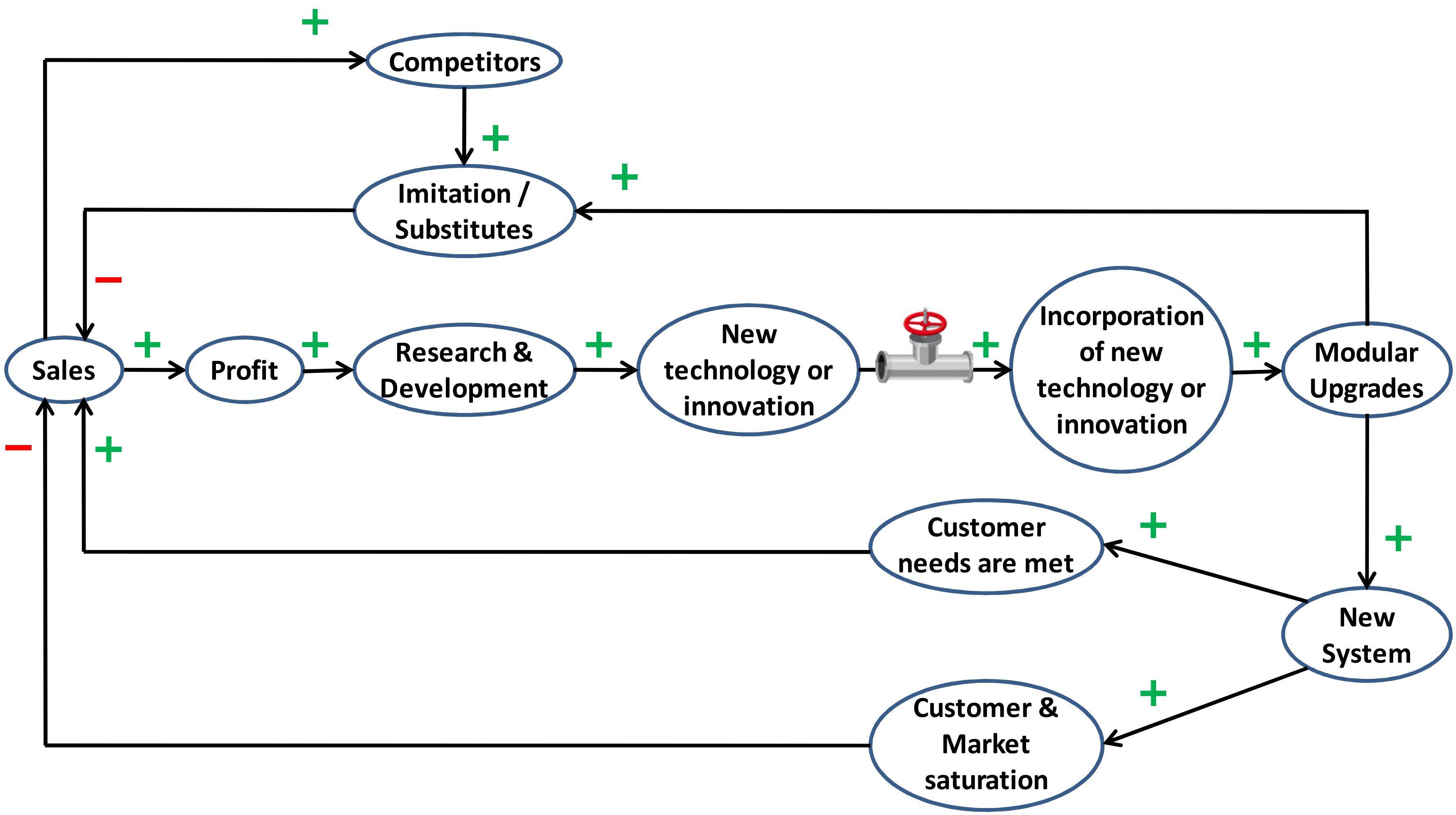


- The **process** is first implementing new technology or innovation to upgrade a module, and then using the upgraded module into the system
- The **structure** is the system
- The **function** is improved performance, cost savings, *and / or* easier or more rapid manufacturing, with the outcome being better system alignment to customer needs

Systemigram Analysis



Causal Loop Analysis



Conclusion – Using Systems Thinking in Modular System Upgrades

- The central role of the systems engineer was better defined when upgrading modular systems through the incorporation of new technologies or innovations
- By balancing various risks, opportunities, and stakeholder interests, it is the systems engineer that dictates the amount and the frequency of the new technologies and innovations that are incorporated

V. Optimization Applied to a Modular System: A Preliminary Model

Attribute Metrics (1)

- Let m be defined as a characteristic of a module
  - A general trait of a module, such that m can be a performance parameter, market advantage, or any other feature that can be attributed to a particular module
  - The set of Modular Attribute Metrics (MAM) can be the different values of m stemming from the variations of the module

$$MAM = \{m_1, m_2, m_3, \dots, m_n\}$$

$$MAM = \{m \mid m \in \mathbb{R}, m \text{ is a measureable attribute of a module}\}$$

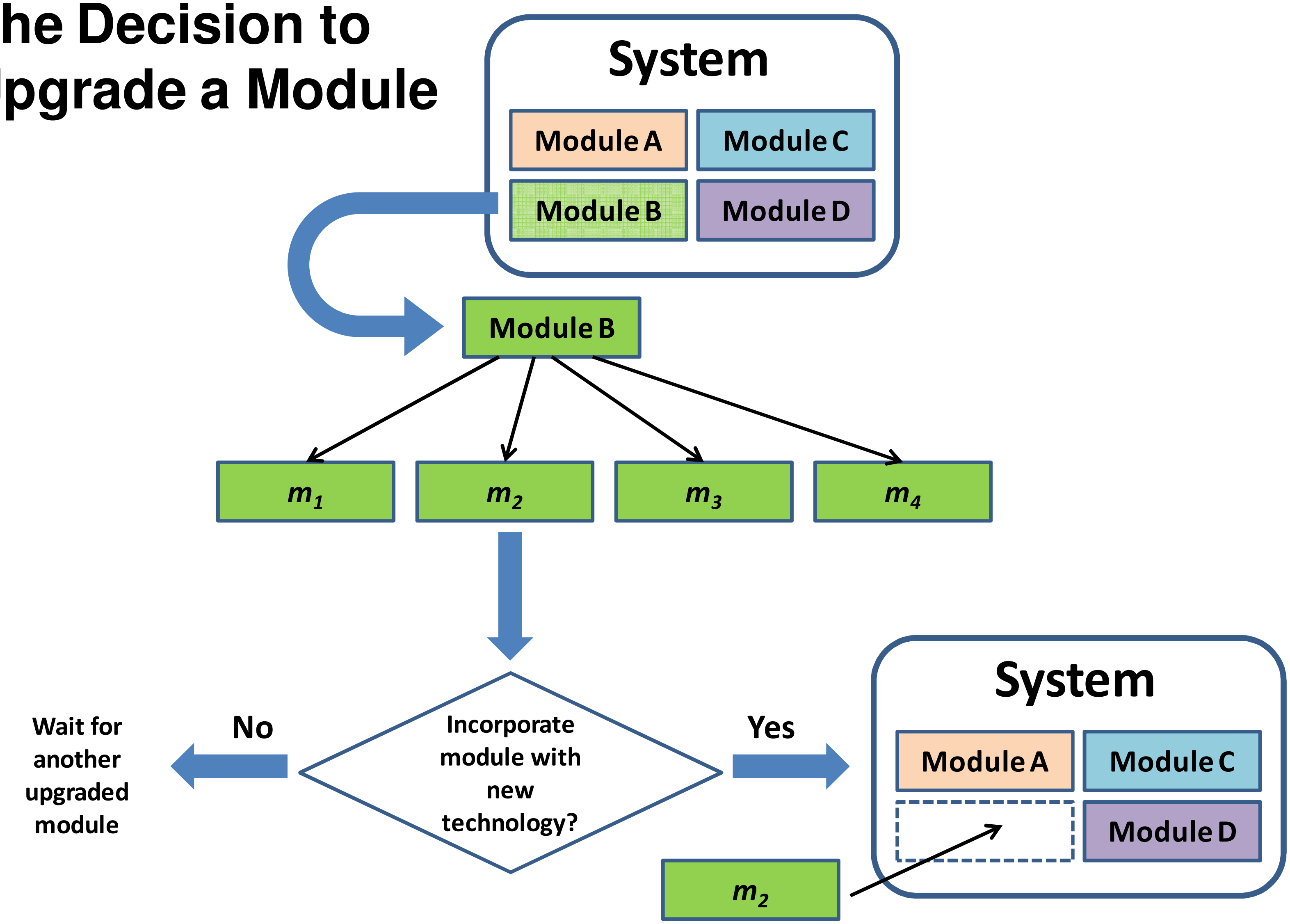
Attribute Metrics (2)

- Let s be defined as a characteristic of a system
  - A characteristic s of the modular system is a function of the modular characteristic m, denoted as $s(m)$
  - The modular trait m produces the system performance metric s

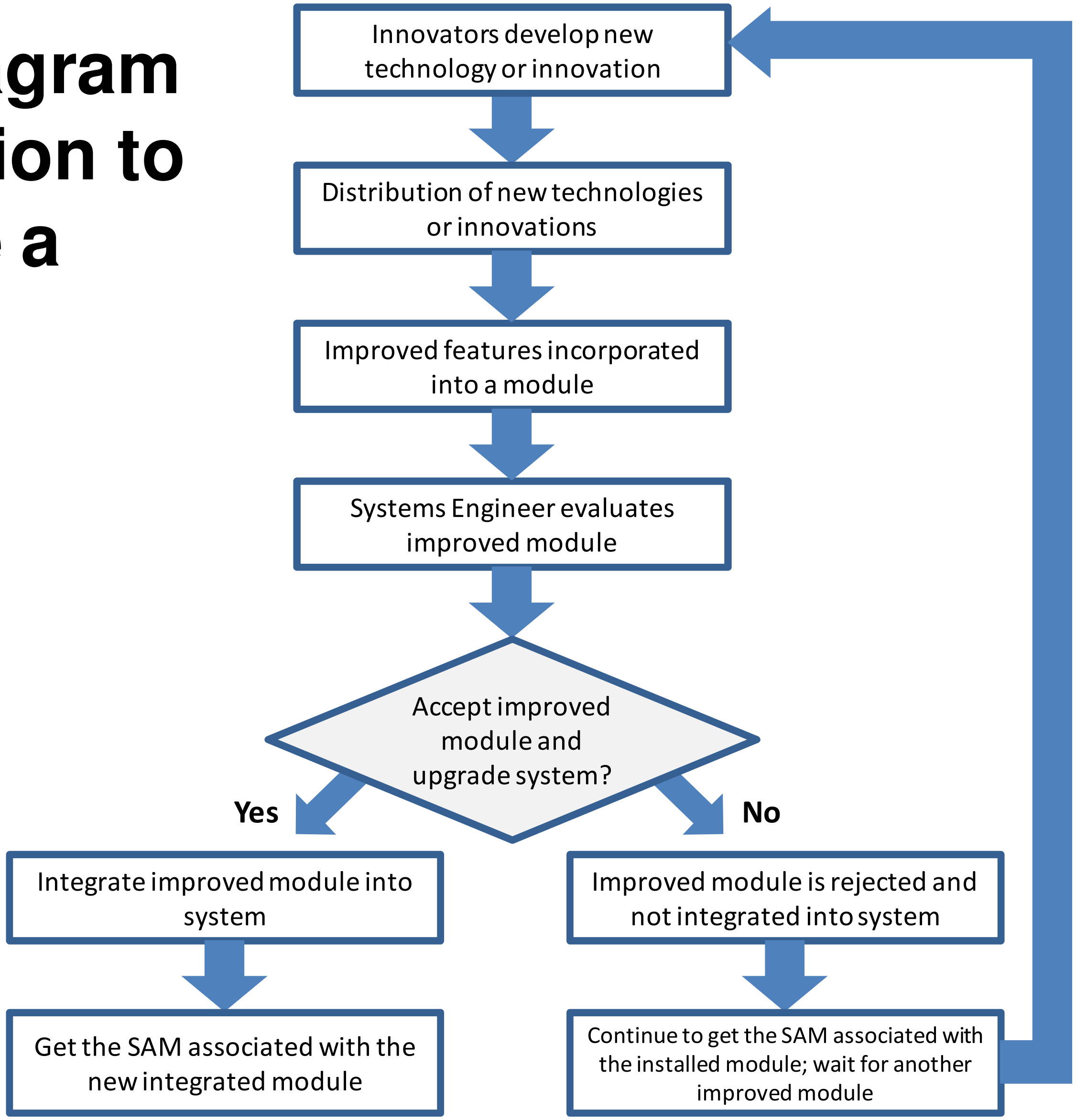
$$SAM = \{s_1, s_2, s_3, \dots, s_n\}$$

$$SAM = \{s \mid s \in \mathbb{R}, m\ is\ a\ measureable\ attribute\ of\ a\ system\}$$

The Decision to Upgrade a Module



Flow Diagram of Decision to Upgrade a Module

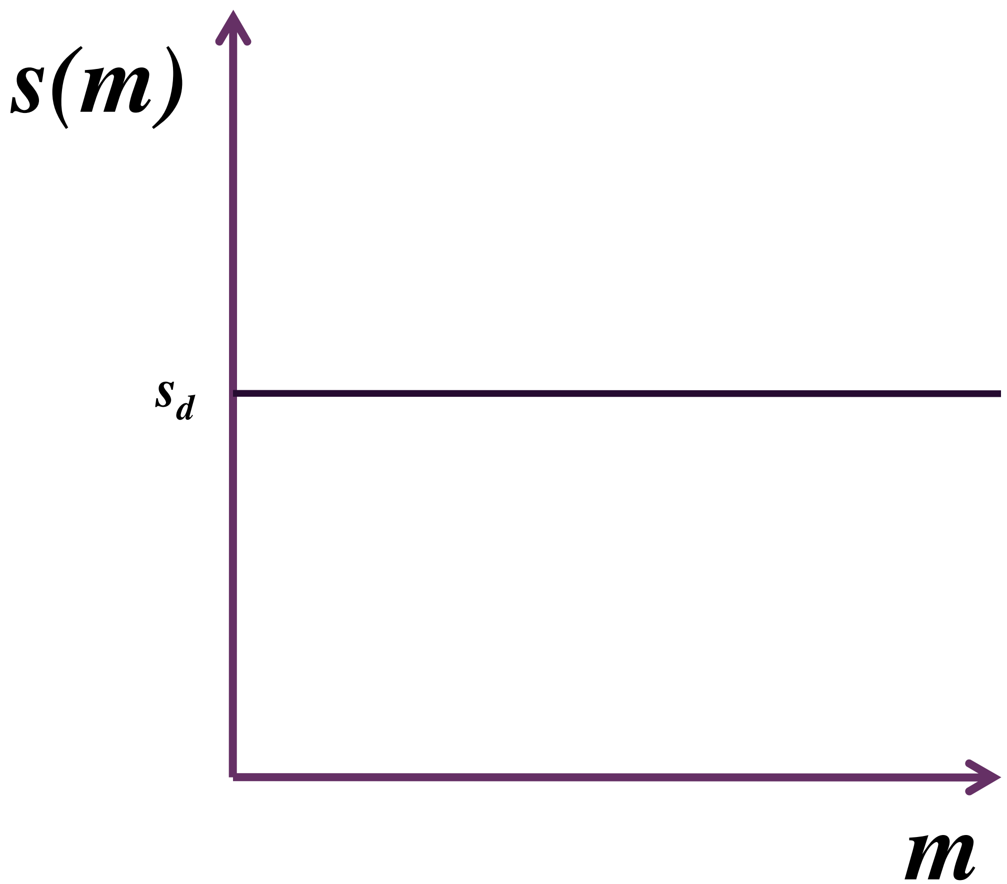


VI. The Optimization Strategy

The “No Upgrades” Approach

- Systems Engineer refuses all module upgrades
- Instead, he does not want to upgrade the system and always uses the pre-existing module design in the current system
- Hence, the system always yields the same system performance parameter s_d (the d stands for default) no matter what module parameter m is available to the system
- The pre-existing module m_d that yields the system performance s_d will always be used in the extreme “no upgrades” approach
- Mathematically, $s(m) = s(m_d) = s_d$ for all m

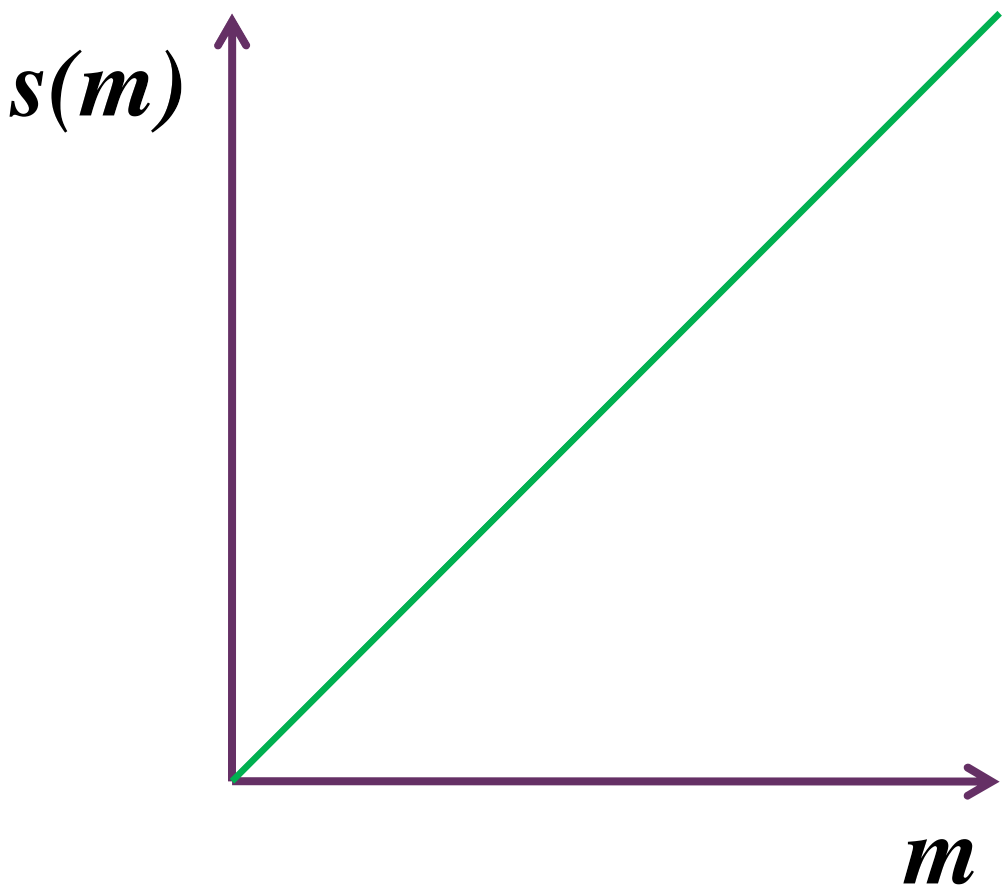
The "No Upgrades" Approach



The "Always Upgrade" Approach

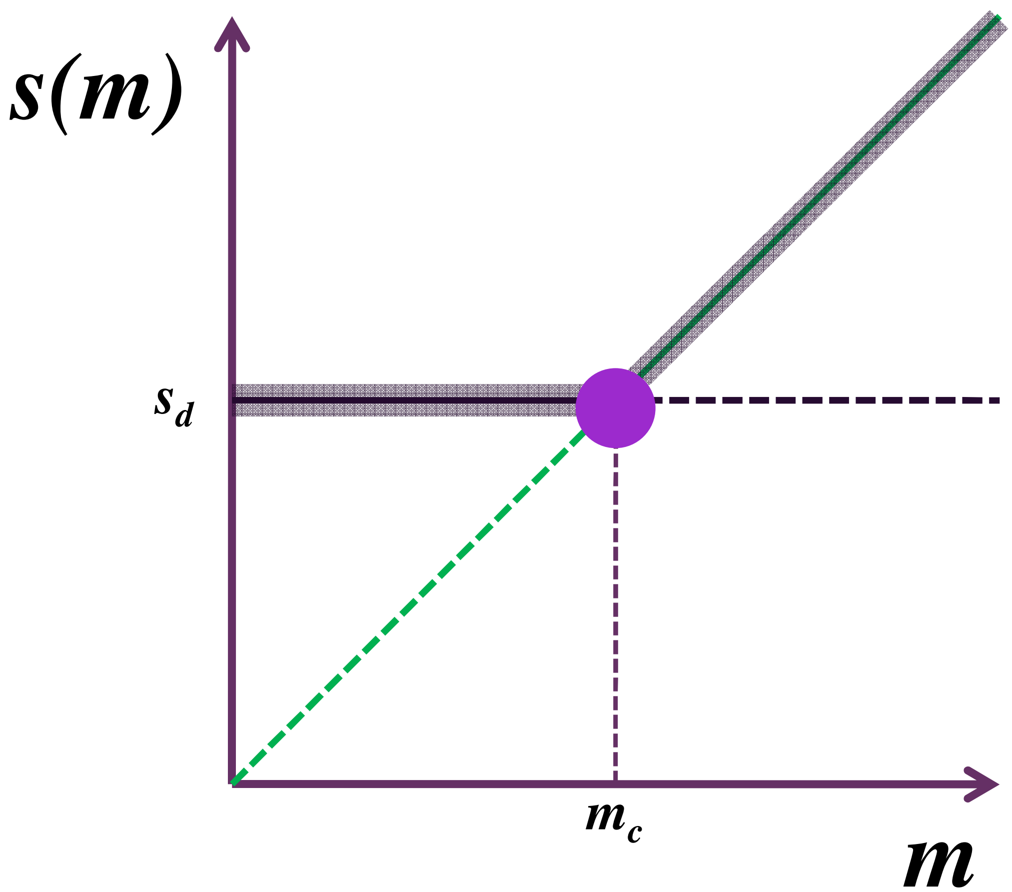
- Systems Engineer always incorporates a module upgrade if and when it becomes available
- For simplicity, consider a linear relationship
  - An improvement in the module performance m will yield a corresponding proportional improvement in system performance s
  - Assume a line with a slope of 1
  - Mathematically, $s(m) = m$ for all m
- The more complicated cases where the shape of $s(m)$ approaches an asymptote and plateaus as m increases, or increases exponentially, or has a Poisson Distribution shape, will be discussed later

The “Always Upgrade” Approach



The Hybrid Approach

- Combines both “no upgrades” and “always upgrade” approaches by choosing the **maximum** of both approaches



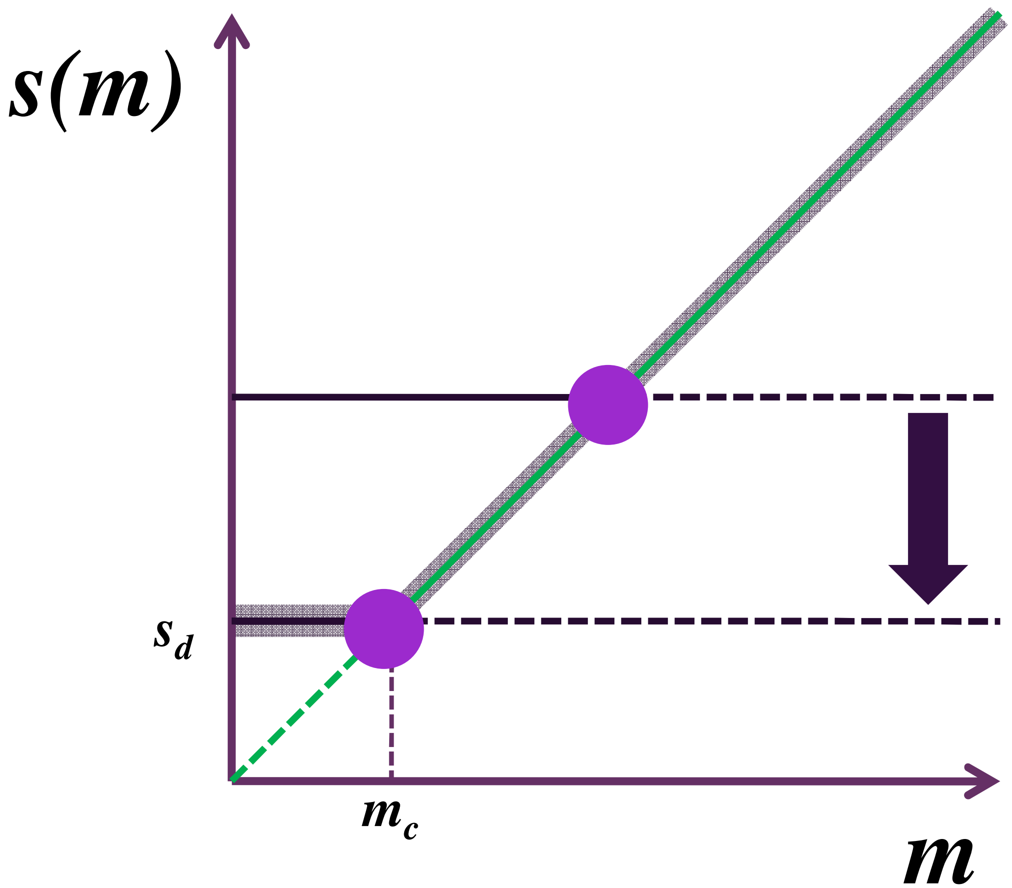
VII. The m_c Value

The m_c Value

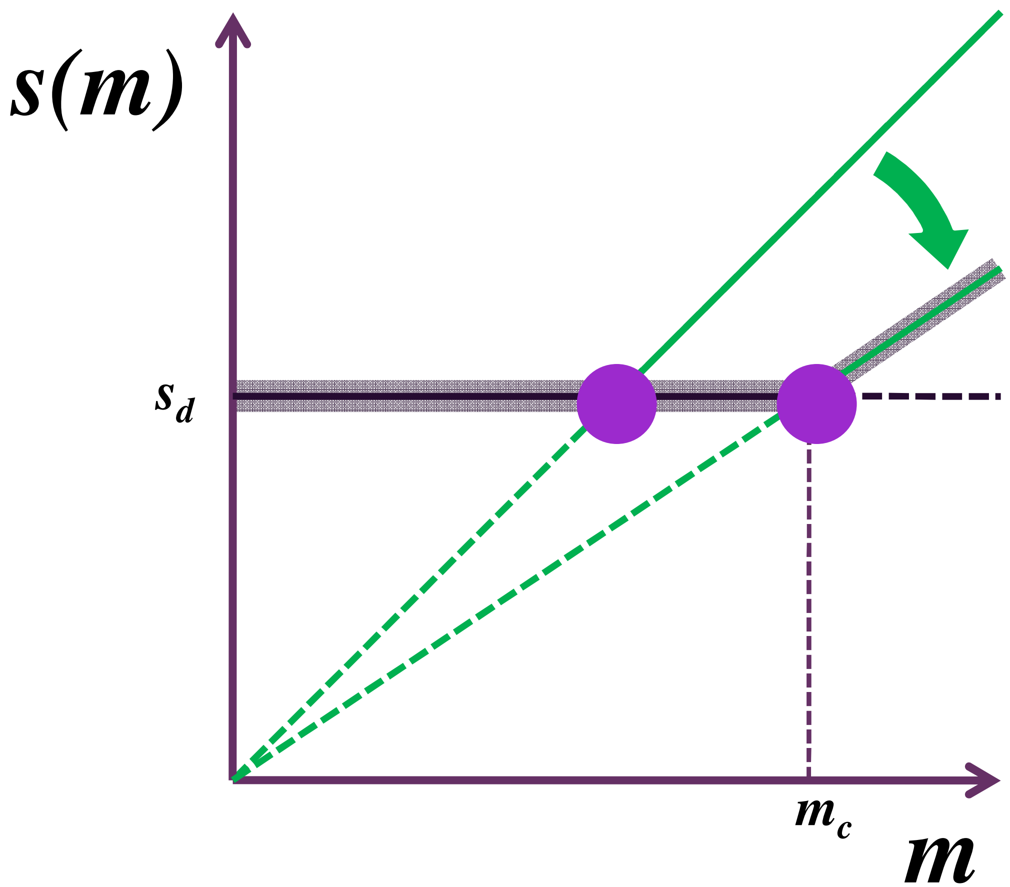
- For m less than m_c, the “no upgrades” approach yields a better system performance than the “always upgrade” approach
- For m greater than m_c, the “always upgrade” approach yields a better system performance than the “no upgrades” approach
- Let Ω be the optimization strategy that is the maximum of the “no upgrades” and “always upgrade” system performances

$$\Omega = \begin{cases} \text{"no upgrades"}\ approach, & for \quad m < m_c \\ \text{"always upgrades"}\ approach, & for \quad m \geq m_c \end{cases}$$

Analyzing m_c Using OFAT – lowering m_c



Analyzing m_c Using OFAT – increasing m_c



Summary of OFAT changes to m_c

Changes		Result
δ of $s(m) = \delta \times m$	s_d	m_c
↑	—	↓
↓	—	↑
—	↑	↑
—	↓	↓

VIII. Conclusion

- This research focuses on a systems engineering approach to the incorporation of new technologies and innovations in modular system upgrades
- Systems thinking concepts of stakeholder, shaping forces, conceptigan, and systemigram analyses are employed to identify the critical factors involved in a modular system upgrade
- Then, the use of search optimization techniques is proposed to explore which new innovation or technology to implement in a modular system upgrade amid many options
- Moving forward, the research effort will focus on refining the preliminary optimization model
  - Variables that shift the critical parameter m_c will be explored, since m_c is a point of reference for the SE on whether to upgrade a module or not
  - Real-life examples and applications of the optimization model will be performed.