# **The Dynamics of Product Commonality:** implications of the circular causality between product and firm structures

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## Abstract
*Companies designing and manufacturing products are trying to decide whether or not, and how, they could adopt modularization strategies to achieve the same functionality and portfolio of products with fewer parts. Existing literature has identified three issues that have yet to be adequately solved: having a holistic approach, studying the risks and trade-offs, and modularity over time. Building on existing literature I formulate an endogenous theory that addresses these three issues and shows how firms migrate towards increasing or decreasing commonality in their product designs. Central to the dynamic behaviour is the circular causality between product and organizational structures. Through simulation experiments and model analysis I also derive insights that imply situations where more effort is needed to gain the sustained benefits of commonality. This study implies that the success of modularization efforts lies in the hands of the firm more so than the market in which the firm operates.*

Keywords: product commonality, modularization, dynamics, over time

## Introduction
Design and manufacturing companies managing a portfolio of products are awakening to the realization that they have a “hell of a lot” of items on their Bill of Materials. The list of parts and sub-components needed to manufacture their end products is longer than what they see as necessary or ideal. The reuse and sharing of components, manufacturing processes, and other resources across a number of products seems like an easy way to improve profitability. Making different parts for different products is seen to create unnecessary costs when the parts have essentially the same functionality. Hence, many companies are trying to decide whether or not, and how, they could adopt a modularization strategy to achieve the same functionality and portfolio of products with fewer parts.

Modularization facilitates the standardization of parts and components by decomposing products into subassemblies and components (Gershenson et al. 2003) that can be used as common elements across a range of products. The concept of modularization is highly related to product platforms as the latter refers to common structures shared by several products or from which derivative products can be efficiently developed and produced (Jiao et al. 2007). The potential benefits of product modularization have been widely researched and advocated in the engineering literature (Gershenson et al. 2003). There are numerous potential benefits to product design, development, production

(Ulrich 1994), process and supply chain management, customer attraction, fleet management, maintenance (Jiao et al. 2007) and everything in between. It is not surprising that, those not yet utilizing are considering modularization and product platform strategies. Existing theory has, however, struggled on three issues relating to modularization. These issues have yet to be adequately solved in the engineering and management fields but which – as argued in this paper – are highly suited for a system dynamics approach. These issues are the need: to have a holistic approach, to study the risks and trade-offs, and to study modularity over time.

***A holistic approach***

Holmqvist & Persson (2004) identify that the literature considering modularization from a holistic point-of-view is rather limited. Jiao et al. (2007) also point out that product family design needs to incorporate a holistic view. What are needed are system-wide solutions that also account other aspects along with the direct economical evaluation. Modularization does not affect product structure alone, but it also affects organizational structure. Brusoni & Prencipe (2001) argue that the diffusion of modularity as a design strategy is accompanied by an increasing division of labour across firms at the product level. This demands interactive management of the many actors and activities involved. The development of platform-based product families requires cross-functional understanding (Halman et al., 2003). Realizing this, researchers in the engineering field have begun to integrate different tools in an effort to gain a more holistic approach (see e.g. Simpson et al. 2012). The challenge is that these tools are designed to support some aspects in platform-based product development and not to simultaneously account for multiple aspects. Jose & Tollenaere (2005) even point out that the methods for product platform development are not practical and future methods should consider many lifecycle factors and activities in an integral manner.

***Risks and trade-offs***

Halman et al. (2003) identify that the risks related to product family development have not been addressed widely in literature and state that a better understanding of the trade-offs involved is needed. Boas et al. (2012) go as far as to state that the literature has a distinctly positive bias towards the benefits of commonality. Gershenson et al. (2003) stress that the benefits need to be verified and validated scientifically. With product design changes affecting many organizational units within and outside a firm, modularization creates many risks. Loch et al. (2003) find that marginal local improvements in complex designs can cause much greater disruptions for the entire system.

***Modularity over time***

Pasche & Persson (2012) elucidate how product and organizational structures co-evolve – mutually influencing each other – and how that might relate to the ability to maintain modularity over time. Modularization strategy should not be just a periodic effort to analyse product design but a continuous process that exploits opportunities as they emerge. Fixson (2007) mentions that studies that follow systems over time appear very promising and the best solution of matching product and organizational structures might be dynamic. Holmqvist & Persson (2004) argue that even if modules are designed in cross-functional teams, the cross-functional work must be continued during the products whole lifecycle or the benefits of modularity could erode.

These shortfalls in research also translate into practise. Commonality is not always easy to achieve nor is it always the right thing to do. Hansen & Sun (2010) find that in practice, many companies fail to reach the expected benefits of modularization. Holmqvist & Persson (2004) find that many companies seem to fail in their modularization efforts partly because they underestimate the effects modularization has on different organizational functions. Case studies (Boas et al. 2012) indicate that commonality tends to decline over time and some systems tend to migrate towards decreasing modularity (Schilling 2000).

This paper will focus on the dynamic effects and potential unintended consequences associated with trying to reduce parts through modularization and commonality. It is an effort to assess in advance the likely impact and pitfalls of the modularization strategy. This research will not offer any new empirical data relating to implementation. I will, however, derive new insights by addressing the previously mentioned issues – issues that researcher in the engineering and management field have themselves identified – with a well suited approach. Evidently, with the well suited approach to addressing the dynamics of commonality, I am referring to system dynamics. Through the approach, I will build a holistic view of how commonality develops over time and show how some firms gain the sustained benefits of commonality while others do not. The result is an endogenous (Richardson, 2011) theory of how firms migrate towards increasing or decreasing commonality in their product designs.

## Methodology

To study the dynamics of commonality I have adopted the firm as the unit of analysis. A more traditional approach in the system dynamics literature has been to use projects as the unit of analysis in the studies relating to product research and development (Montaño 2011) (Ford & Sterman 1998) (Roberts 1962). The change from project to firm level, allows us to account for the unsolved issues described in the engineering and management literature relating to product commonality and modularization. For instance, it allows us to study the managerial implications of modularization efforts beyond the scope of the initial modularization efforts. As a result, there is less emphasis on the management of design and development projects even though modularization can in many cases be seen as project based.

From the relevant literature I have identified three main feedbacks: design reinforcement, change propagation, and product differentiation. Using these three feedbacks (shown in Figure 1) as my starting point, I have formulated a simulation model to test and analyse the behaviour these structures potentially generate. Readers desiring a more in-depth and formal review of the formulations and additional structures are referred to the accompanied simulation model, also available from the author upon request.

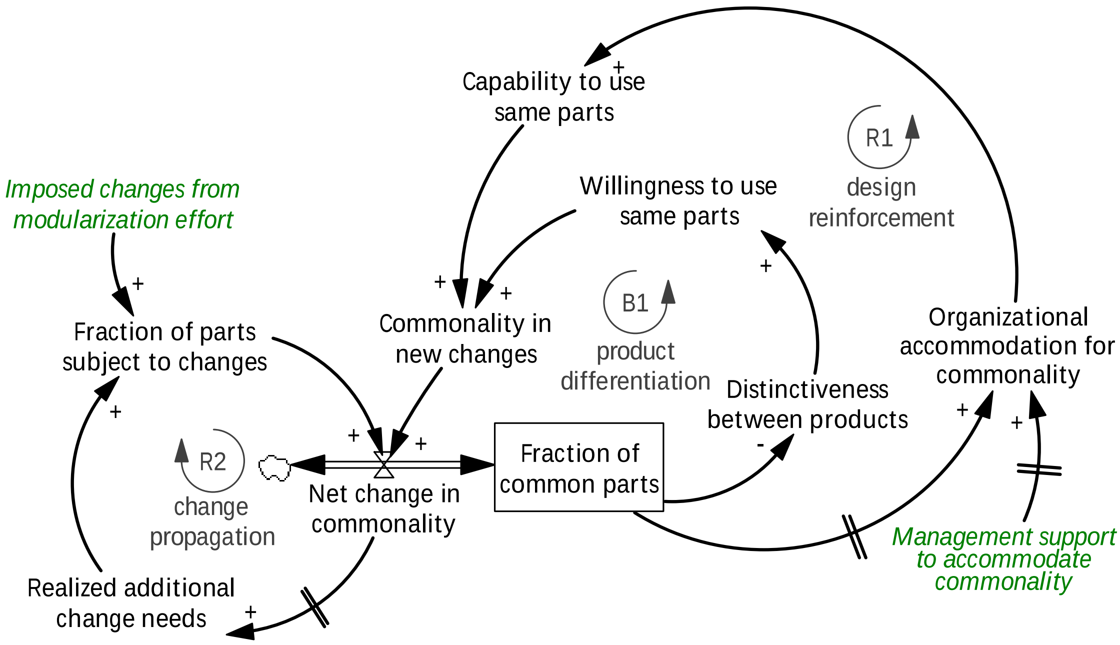


*__Figure 1.__ Main feedbacks affecting commonality – the fraction of common parts in a product portfolio. For a more in-depth view of the formulations and additional structures refer to the accompanied simulation model.*

### *R1: design reinforcement*

The central process in the model is the co-evolution of product and organizational design. I label it *R1: design reinforcement* as they form a reinforcing feedback structure where the commonality of products (*fraction of common parts*) influences the organizational structures and processes (*accommodation for communality*) that form the capability to create commonality in products. The more commonality in products the more practices and processes to accommodate commonality will emerge. The more accommodation for commonality the more commonality there will be in new product changes – closing the loop. The loop can also take a turn towards diminishing commonality if more turns to less.

The co-evolution of product and organizational design is widely acknowledged in the existing literature. Gulati and Eppinger (1996) observe that firms simultaneously exhibit mechanisms where product structures affect organizational structures and organizational structures affect product structures. Product architecture, for example, determines organizational communication patterns, and organizational skills and capabilities affect product architecture. Miguel (2005) notes that modularity in organization relates to processes, management, and procedures that are adopted or used to accommodate modular production. Sako (2003) also acknowledge the co-evolution and argues that organizations constrain shifts in product architecture. She adds that if such shifts occur, they are likely to be slow and met with internal organizational inertia and resistance because of the effect that they have on labour, capabilities, and power. Staudenmayer et al. (2005) argue that firms can exhibit lack of control over the definition of their own products as standard external interfaces impose constraints. Colfer & Baldwin (2010) find that modular architectures can lead to new relationships between the structure of the technical system and the organizational ties between developers. Empirical evidence shows that under the condition of product architecture stability the degree of coupling between components varies directly with the degree of coupling of organizations (Cabigiosu & Camuffo 2012).

The way I have modelled the nature and strength of the co-evolution contains certain important assumptions – as do all explicit formulations that attempt to quantify verbal presentations. First, the way *fraction of common parts* affects *accommodation for commonality* is formulated; I assume that organizational structure gradually adjusts towards the structure of the product. This means that if commonality stays stable, given enough time, firms will develop organizational structures and practices to accommodate the degree of commonality in the product design. Second, the way *accommodation for commonality* affects *fraction of common parts* is formulated; I assume that when accommodation is non-existent, small changes to accommodate commonality have little effect in creating commonality in new designs. Also, when accommodation is near its maximum, small changes that reduce accommodation have little effect in decreasing commonality of new designs. When accommodation for commonality is somewhere in between, changes have a bigger change on commonality of new design.

***R2: change propagation***

In modular architecture, changes to one part of the design do not trigger compensating changes in other components (Colfer & Baldwin 2010). A change to the level of modularity, however, can trigger a host of other changes. I label it *R2: change propagation* as it forms the second reinforcing feedback. *Changes in commonality* potentially create additional opportunities and change needs. These additional changes in turn may or may not, depending whether or not they change the level of commonality, induce other changes.

Cameron & Crawley (2014) note that product platforms can create opportunities for future variants – opportunities which are only revealed over time. As modularization has numerous potential benefits (Ulrich 1994) (Jiao et al. 2007) and trade-offs (Sako 2003) in different organizational units, changes that affect the design rules and module boundaries can create propagating opportunities or needs in other units. Changes affecting commonality can occur in planning, development, manufacturing, or operations (Boas et al. 2012). Case studies (Halman et al. 2003) show that not all platforms are planned or defined at the beginning of product development, but rather emerge later in the product life cycle. Different trade-offs at different stages of modularity (Sako 2003) can create pressure to induce design rule, module interface and commonality changes long after the initial modularization efforts.

Loch et al. (2003) find that marginal local improvements in complex designs can cause much greater disruptions for the entire system. Modularization creates new module boundaries and, therefore, also new transaction locations (Baldwin 2008). Cormican & O’Sullivan (2004) also point out that development team members represent different disciplines, different organisations, and sometimes different countries. These can create barriers and delay the propagation of shared understanding.

***B1: product differentiation***

One of the most common mentioned trade-off to the utilization of same components between different products is the loss in product differentiation. As the *fraction of same* *parts* increases, products increasingly begin to look alike and the willingness to further utilize same parts diminishes. I label it *B1: product differentiation* as it forms the first balancing loop that sets limitation to the level of commonality firms will want to achieve. There is a level of commonality below 100% at which the products resemble one another to the extent that, no matter how beneficial additional commonality or how accommodating organizational structures are, firms will not induce any additional commonality.

Kim & Chhajed (2001) show that in many cases identical feature levels increase the perceived similarity between original and extension products. Product commonality and distinctiveness create a trade-off between product synergies and cannibalization (Robertson & Ulrich 1998). To a certain extent, marketing may gain from commonality in the form of strong brand identify (Halman et al. 2003), but too much commonality can have an adverse effect (Simpson et al. 2006).

***Decision variables***

In the model, there are two decisions that firms make relating to the modularization efforts; allocate engineering time to modular design efforts, and facilitate cross-functional interfirm design meetings and other processes to accommodate modularization. In the model, these two decisions affect two different parts of the system (see Figure 1). Engineering effort affects the *fraction of parts subject to change.* The more effort is put into engineering the greater amount of parts incur changes. Management support affects the organizational *accommodation for commonality*. Accommodation for commonality indicates the level to which the firm's organizational structures and patterns support commonality. This affects the way people communicate, exchange business and technological information, coordinate decisions, and prioritize efforts to support the use of same parts between products. The more effort is put on accommodating commonality the more commonality there will be in new changes. Both decision areas have the dimensions of intensity and duration – how much effort and for how long.

## Results

Two simulation runs highlight the interesting behaviour generated by the feedback loops. In one scenario the firm migrates towards decreasing, and in the other towards increasing, levels of commonality (see Figure 2). The only difference between the two simulations is one extra month of management support. Engineering and management support efforts start at month 12 in both cases. In the scenario where commonality ends at a high sustained level, management support continues till half way through month 19. In the scenario where commonality continues to decrease, management support is ceased only one month earlier at half way through month 18. There is a nonlinear nature to the effects of management support where similar situation exhibit totally different modes of behaviour. Furthermore, there are additional insights that can be derived from model analysis and simulation experiments. I present these insights as proposition that relate to the dynamic nature of commonality and imply where more management effort in accommodating commonality is needed.

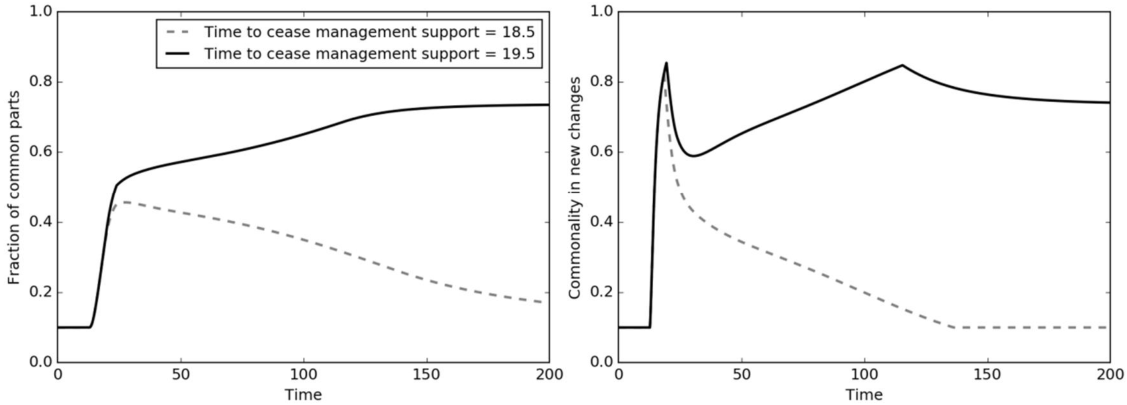


***Figure 2.*** *Two simulations that show a sustained and a divergent behavior of product commonality. The only difference between the two simulations is one extra month of management support.*

> ***Proposition 1****: There is a tipping point where small additional efforts change the behaviour of commonality from divergent to sustained.*

Before the tipping point, management effort is always needed to combat commonality erosion, but after it the circular causality between product and organizational design will drive commonality even without management support. The reinforcing mechanism (*R1: design reinforcement*) lies at the heart of the explanation. As in all reinforcing processes, a small change in the accommodation for commonality builds on itself. In the scenario where management support ends one month earlier, the reinforcing circular causality between product and organizational design works in a vicious direction.

During management support, organizational structures that support commonality are created and the level of commonality in new product changes is high. As a result, the fraction of common parts rises rapidly. When the support ends organizational structures are no longer artificially maintained and they begin to conform to the structure of the products. Organizational processes and communication, that are not constantly utilized and maintained, dissipate. The commonality in new changes rapidly decreases as the accommodation for commonality dissipates. The decreasing product commonality then creates even more pressure for organizational structures accommodating commonality to dissipate. The cycle will then continue in the direction – diverging commonality.

Maintaining support long enough will, however, turn the vicious cycle into a virtuous one. When product commonality rises high enough, the pressure for dissipating organizational structures is smaller than the capability to create commonality in products. Products then become more modular and share more parts further reinforcing the organizational processes and communication that create further commonality. The cycle will then continue in the direction increasing commonality until the balancing effects of product differentiation begin to dominate. The tipping point is the point where the co-evolution of product and organizational designs turn from a vicious to a virtuous cycle. Firms sceptical and conservative in their use of resources and investments in efforts to induce commonality may – as a result – find themselves failing.

***Proposition 2**: Firms in which organizational structures and processes can change quickly will find it harder to sustain commonality.*

If organizational structures change quickly they are fast to erode the accommodation for commonality that has been built by management efforts. The organizational structures and processes that have been put in place to drive commonality will fade fast after management support ends. To compensate for the faster erosion, the duration (or intensity) of management support needs to be longer. Figure 3 shows how the speed at which organizational structures change affects the duration of management support needed to reach the tipping point. When the product structure does not change as fast it introduces pressure for organizational structure to conform to its level of modularity and commonality.

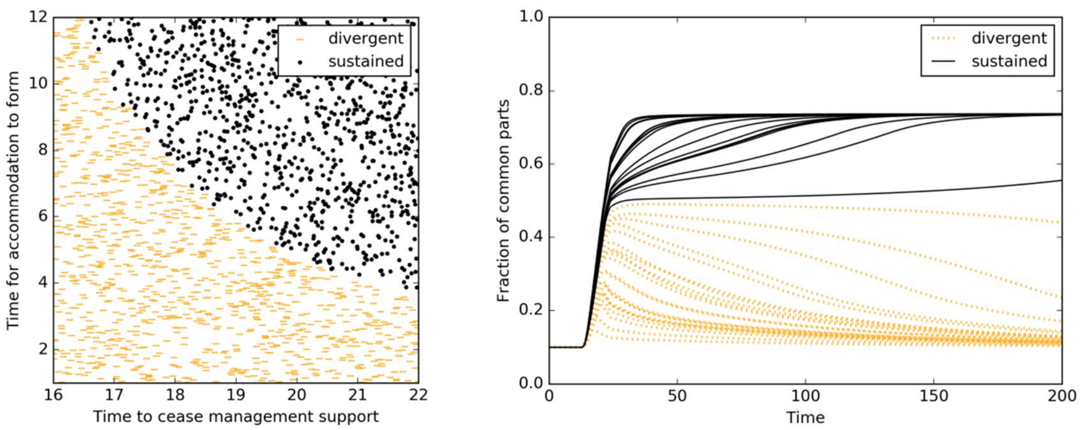


***Figure 3.** Results of 2000 Monte Carlo simulations by varying the time management support ends and the average time to form organizational structures that accommodate commonality. To avoid cluttering, the right figure shows the categorization of every 50th simulation.*

***Proposition 3**: Firms that are able to realize additional change needs in products faster will find it easier to sustain commonality.*

Realizing the additional ideas and need for changes faster means that changes can be implemented while there is still high levels of support for accommodating commonality. This has the potential to achieve the tipping point of commonality much faster. Figure 4 shows how the time in which additional changes needs are realized affects the duration of management support needed to reach the tipping point.

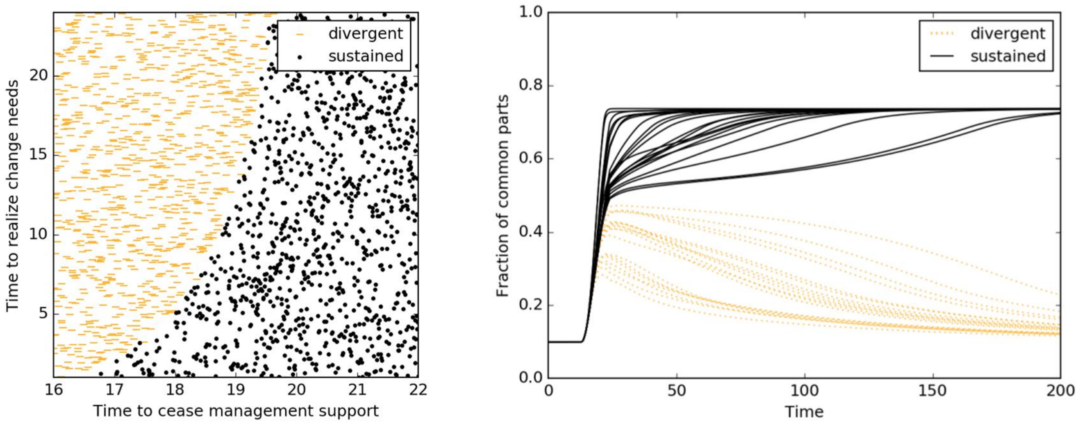


***Figure 4.*** *Results of 2000 Monte Carlo simulations by varying the time management support ends and the average time to realize change needs. To avoid cluttering, the right figure shows the categorization of every 50th simulation.*

> ***Proposition 4****: Firms that have the widest potential benefits relating to commonality can also erode their commonality the fastest.*

Firms that have a multitude of links between organizational units and product structure potentially have greater opportunities for exploiting modularity. Firms can then leverage commonality in product development, production, process and supply chain management, maintenance, and many other activities. The multitude of links, also imply that there is the potential for changes to propagate to a greater extent (through the reinforcing feedback *R2: change propagation*). As there is a higher probability to incur additional change, commonality can erode or build faster depending on the level of commonality in new design changes. Same applies to naturally rapid changing industries where the naturally induced product changes affect the speed at which the divergence or convergence towards commonality happens.

Simulations in Figure 5 show that the tipping point is less sensitive to the variation in additional change needs than to the variation in factors of previous propositions. Additional change needs do, however, make the dynamics playout faster. It makes a bad situation worse and a good situation better. Realizing additional change needs can potentially turn otherwise divergent situation into a sustained one but only nearer to the tipping point. Hence, it is better to realize additional changes faster than just trying to realize more of them.

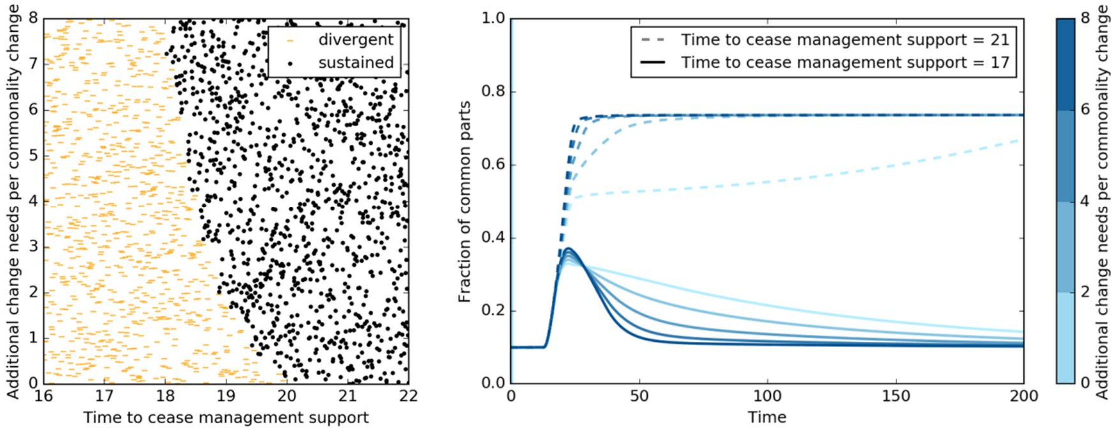


***Figure 5.*** *Results of 2000 Monte Carlo simulations by varying the time management support ends and the amount of additional changes induced by changes in commonality. The right figure shows the accelerating effect of additional change needs when away from the tipping point.*

## Conclusions

The constructed simulation model explains how some firms might face systematic downward pressure on commonality while others continue to reap its benefits. The conclusion that similar firms can exhibit quite different dynamics in the behaviour and the long term success of modularization efforts is consistent with the existing theory on improvement program implementation (Repenning 2002).

Through simulation experiments and model analysis I also derived insights that imply situations where more effort is needed to gain the sustained benefits of commonality. These build on the existing literature on product engineering and management by introducing a more holistic approach that simultaneously links potential benefits and trade-offs, and show how they relate to commonality over time. However, the propositions implied by the simulation experiments still need to be tested and validated with empirical evidence. Those of you familiar with the modularization, commonality, and product platform literatures will find that there are numerous potential benefits and trade-offs that are not captured in the model. This is not to say that they cannot be but rather to say that they have yet to be.

Managers may find it empowering (Richardson 2011) that this study implies that the success of modularization efforts lies in their hands. Their decisions and efforts are what contribute to the problem and its solution. Cameron & Crawley (2014) also introduce similar insight as in their understanding “divergence varies much more strongly in response to a firm’s management capabilities than in response to the market in which the firm operates”.

Even though the propositions are derived from the context of product design, they are applicable to services as well. The propositions can be reasonably applied to services that are formed through the changing interaction between multiple individuals. If changes in the service design create discrepancy between the service structures and organizational structures, there will be pressure for one to migrate towards the other.

One should not look at designing products or services as independent from designing organizational structures and processes.

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