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What is Modularization?
A Literature-Grounded Ontology

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Short Abstract and Keywords (English version)

This work consists firstly in a collection of the literature upon the modularization concept. The collection is obtained by researching through a bibliographic database, and is subsequently reviewed to highlight the trending topics of the literature. This permitted to reach the second objective of the work, that is to say the formulation of the literature-grounded ontology of the modularization. The ontology contains the extended definition of the concept, the concept's boundaries, and the enabling factors and effects of the concept. A coding scheme has been implemented to connect the information retrieved in the papers to a general framework, and has then been used to frame the concept with its most relevant features. Despite all the research that has been published, there is still no general definition of the concept among the economic world, even if the researchers mentioned most of the aspects characterizing the modularization concept. This work aims to open new research horizons and induce new practices regard to the modularization concept, breaking the borders between the different sectors of economy.

Keywords: Modularization, Life cycle, Ontology, Literature review, Modularity

Short Abstract and Keywords (Italian version)

Questo lavoro contiene innanzitutto la raccolta degli articoli presenti in letteratura riguardo all'argomento della modularizzazione. La raccolta è stata ottenuta dalla ricerca degli articoli in una base dati bibliografica, ed è stata quindi revisionata affinché siano evidenziati i temi di maggior rilevanza presenti in letteratura. Ciò ha permesso di raggiungere il secondo obiettivo del lavoro, ovvero quello di formulare un'ontologia basata sulla letteratura del concetto di modularizzazione. L'ontologia contiene la definizione estesa del concetto, gli elementi che ne costituiscono la frontiera, i fattori abilitanti e gli effetti del concetto stesso. Uno schema di coding è stato implementato per connettere le informazioni estratte dagli articoli ad un framework generale, e questo stumento è stato usato per inquadrare il concetto con le sue caratteristiche più rilevanti. Malgrado la mole di ricerche pubblicate, non esiste in letteratura una definizione generica del concetto riguardante l'intero mondo economico, benché i ricercatori abbiano menzionato la maggior parte degli aspetti caratteristici del concetto di modularizzazione. Lo scopo di questo lavoro è di scoprire nuovi orizzonti di ricerca ed indurre l'uso di nuove appplicazioni del concetto di modularizzazione, andando oltre ai limiti imposti tra i vari settori dell'economia.

Parole chiave: Modularizzazione, Ciclo di vita, Ontologia, Revisione della letteratura, Modularità

Extended Abstract (English version)

Purpose

The purpose of this paper is to introduce a literature-grounded ontology about the conceptualization of the modularization of socio-technical systems with a particular emphasis upon the life cycle perspective.

Methodology

The work arises from a collection of 160 papers, which contents have been synthetized by using a coded database, in order to categorize the articles' information into a well-defined framework. The literature is then reviewed, capitalizing on the sub-categorization of the database and the definition of the coding's framework, to highlight the aspects of modularization that could help to shape an ontology of the concept. Therefore, the most interesting features regarding the definition of modularization, its boundaries, and its relations with enabling factors and effects will be brought up to understand what the whole modularization is meaning.

Findings

The review of literature has highlighted the most relevant aspects linked to the modularization issue. As it has been shown, there are plenty of different definitions given by the researchers that are valid in some specific scopes or that partially explain the phenomenon.

The intent here has been to gather the valid and most general properties of modularization, in order to define the concept in its most general meaning. The result is expressed by the following definition:

"Modularization consists in a configuration of a socio-technical system through its architecture breakdown into standard and functional subsystems, which are interfaced to operate together as a whole and may impact on all the system's life cycle. Both its achievement and justification should arise from a life cycle-oriented decision-making process."

The most general and consistent properties that were identified are summed up in the following list:

- System's architecture breakdown into standard and functional subsystems,
- The optimization of the interfaces,
- The various impacts on the system's life cycle,
- The decision making process.

The need of symbiosis among the three following properties is essential to the existence of modularization: architecture breakdown, using standards, and interfaces management. However, the life cycle perspective is advisable, in order to make a decision about modularization, which will be based on the analysis of the concept's impact all along the system's life cycle.

The concept's boundaries have been investigated from the decision maker's point of view, which is represented by the division between the aspects that are out from the decision maker's sphere (external boundaries), the other aspects that depend on the behavior of the decision-maker (internal boundaries), and those aspects that are may pertain to both types. The categories highlighted as major contributors to the concept's boundaries are:

- Context, which is divided into the concentric contexts of firm, market and global context;
- Architecture that is mainly an internal boundary of modularization, because it depends only on the system's features;
- Life cycle, which is divided into different stages (concept, design, development/construction, utilization, phase-out) and concerns both external and internal boundaries,
- Supply chain, where aspects concerning suppliers, buyers, or both, are told apart;
- Capabilities that are essentially represented as external boundaries, because these are the only capabilities that hold back from modularization;
- Communication/Interfacing, which are divided into context-level aspects (external boundaries), system-level aspects (internal boundaries), and interface-level aspects (which could be both).

Finally, the enabling factors and the effects are listed, in order to sketch a modularization framework, across the interactions between the concept and its most generic surrounding.

The enabling factors are classified under the three main properties a system should specifically define in order to become modularized (architecture breakdown, using standardization, and interfaces management), and four other aspects (Technical aspects/capabilities, Considering the context, Division of work, and Design decisions) that need to be set up well, to enable the modularization.

The effects highlighted are the impacts on **the system's performance** (economics-related, time-related, quality-related, variety-related, flexibility-related, risks-related, efficiency-related, and customization-related) end the other effects, mainly represented by the following categories:

- Capabilities availability, which are sub-divided into four categories: human resources-related, knowledge-related, flexibility-related, and sustainability-related;
- Modeling and decision support tools and practices, which are the instruments that have been used within the modularization, which though are general instruments that may be used in any kind of socio-technical context;
- Innovation practices;
- Supply chain practices;
- Organizational design and practices;
- Strategic management practices.

This list represents any kind of effect that modularization may cause and that may be reused in other different contexts.

Research limitations/implications

The modularization is a concept that should include the creation of a standard procedure that would make it a repeatable instrument to achieve modularity objectives.
Some specific context's characteristics have not been taken into account (maybe because they are less related to the manufacturing industry, which is the literature's most analyzed sector upon the modularization topic):

- The meteorological aspect, which influences the design of the socio-technical system. For example, a power plant would have different characteristics, if the location was tropical rather than if it was polar.
- The geographical aspect that literature mentions barely. This context's characteristic is leading to diverse areas of competence: the political situation, the legislative context, and other local issues may push towards certain decisions, which would interfere in the modularization process.
- The infrastructural aspect is playing a major role in the modularization decisions, especially regarding the development stage
- The social aspects as well are essential to be considered (e.g. the availability of workforce)
- …

The decision maker should evaluate over an in-depth life cycle assessment, which level of modularization is the more convenient for his case. This issue is represented by the tradeoff between the convenience of breaking down the system into little and manageable chunks and the creation of a large number of interfaces.

Even if the literature covers a large number of scopes, the concept is not yet completely determined. There are still areas (e.g. among the life cycle or the supply chain) that are not yet exhaustively studied by the researchers.

Moreover, the effects of modularization are superficially known: every decision that is required by modularization leads to a chain of events that impacts on many aspects of the system's properties and surroundings.

A limit to the modularization concept is represented by the superficial knowledge of the mechanisms that govern the system's performance and other effects. For example, design decisions that impact on system's life cycle stages have to be determined after achieving an in-depth analysis of the downstream stages (development, utilization, and phase-out). Therefore, knowing what happens after the decision helps to take the best decision.

Originality/value

The concept should be faced as a top down decomposition into modules, instead of a bottom up assembly process (clustering is a recurring topic among the literature).

The introduction of the systematic concept's assessment on various fronts (e.g. life cycle, supply chain, firm's organization, workforce, knowledge, etc.) is giving to the concept a complete new dimension, which leads to better modularization practices.

Extended Abstract (Italian version)

Scopo

Lo scopo di questo lavoro è di proporre una ontologia fondata sulla revisione della letteratura, riguardo alla concettualizzazione della modularizzazione di sistemi sociotecnici, con un enfasi particolare sulla prospettiva di ciclo di vita.

Metodologia

Il lavoro nasce da una raccolta di 160 articoli i quali sono stati riassunti usando un database codificato, affinché sia possibile categorizzare le informazioni estratte dagli articoli in un framework definito ad hoc. La letteratura è stata quindi revisionata, usando le sottocategorie del database e la definizione del framework di coding, affinché sia possibile evidenziare gli aspetti della modularizzazione che permettono di formare una ontologia del concetto. Le caratteristiche più interessanti riguardo alla definizione di modularizzazione, dei suoi limiti e le relazioni coi fattori abilitanti e gli effetti sono quindi stati rilevati affiché si possa capire cosa significhi il concetto di modularizzazione per intero.

Scoperte

La revisione della letteratura ha permesso di evidenziare gli aspetti più importanti collegati al problema della modularizzazione. Come è stato mostrato, molte definizioni sono state date dai ricercatori, che però difficilmente valgono al di fuori degli scopi specifici predefiniti e spiegano solo in parte il fenomeno.

L'intenzione è stata quella di raccogliere le proprietà valide e più generiche della modularizzazione, in modo che si possa definire il concetto nella maniera più generale possibile. Il risultato è quindi espresso dalla definizione seguente:

"La modularizzazione consiste in una configurazione di un sistema sociotecnico tramite la scomposizione dell'architettura in sottosistemi standard e funzionali, che si interfacciano in modo da operare in un tutt'uno e possono avere impatto su tutto il ciclo di vita del sistema. Sia la sua realizzazione che la sua giustificazione dovrebbero nascere da un processo decisionale orientato al ciclo di vita."

Le proprietà più generali e consistenti identificate sono state riassunte nella lista seguente:

- La scomposizione dell'architettura del sistema in sottosistemi standard e funzionali,
- L'ottimizzazione delle interfacce,
- I vari impatti sul ciclo di vita del sistema,
- Il processo decisionale.

Il bisogno di simbiosi tra le tre proprietà seguenti è essenziale affinché la modularizzazione possa esistere: la scomposizione dell'architettura, l'utilizzo di standard e la gestione delle interfacce. Ciononostante, la prospettiva di ciclo di vita è assolutamente essenziale, affinché si possa prendere una decisione riguardo alla modularizzazione, che si basa sull'analisi degli impatti del concetto lungo l'intero ciclo di vita del sistema.

I limiti del concetto sono stati investigati dal punto di vista del decisore, che è stato rappresentato in modo da separare gli aspetti che sono al di fuori della sfera del decisore (limiti esterni) dagli aspetti che dipendono dalle azioni del decisore (limiti interni), dagli aspetti che appartengono ad entrambe le categorie. Le categorie che sono state evidenziate come quelle che danno il contributo maggiore ai limiti del concetto sono;

- Contesto, che è stato diviso in nei contesti concentrici di impresa, mercato e contesto globale;
- Architettura, che riguarda principalmente limiti interni alla modularizzazione, siccome essa dipende solamente dalle caratteristiche del sistema;
- Ciclo di vita, che si divide nelle diverse fasi (concettuale, progettazione, sviluppo/costruzione, uso, dismissione) e che riguarda sia limiti esterni che limiti interni;
- Supply chain, in cui gli aspetti riguardanti i fornitori, gli acquirenti, oppure entrambi sono evidenziati;
- Competenze, che sono essenzialmente rappresentate nella categoria di limiti esterni, siccome esse sono solamente le competenze che allontanano il decisore dalla modularizzazione;
- Comunicazione/Interfacce, che vengono divise in aspetti di contesto (limiti esterni), aspetti di sistema (limiti interni) ed aspetti di interfaccia (che possono essere sia esterni che interni).

Infine, fattori abilitanti ed effetti sono analizzati, affinché si possa abbozzare un framework di modularizzazione riguardante le interazioni tra il concetto stesso e l'ambiente circostante.

I fattori abilitanti vengono classificati sotto le tre proprietà principali che il sistema deve definire in dettaglio affinché lo si possa definire modularizzato (scomposizione dell'architettura, utilizzo degli standard, gestione delle interfacce), ed altri quattro aspetti (Aspetti tecnici/Competenze, Considerando il contesto, Divisione del lavoro, Decisioni progettuali) che devono essere definite correttamente, affinché la modularizzazione sia abilitata. Gli effetti evidenziati sono gli impatti sulle **performance di sistema** (economiche, relative al tempo, relative alla qualità, relative alla varietà, relative alla flessibilità, relative al rischio, relative all'efficienza, relative alla customizzazione) ed **altri effetti**, rappresentati principalmente dalle categorie seguenti:

- La disponibilità di competenze, categoria che viene suddivisa in quattro sotto categorie: risorse umane, conoscenza, flessibilità e sostenibilità;
- Strumenti e tecniche di modellazione e di supporto alle decisioni: sono quelli utilizzati nel contesto della modularizzazione, che però sono generici e quindi possono essere usati in qualsiasi tipo di contesto sociotecnico;
- Tecniche innovative;
- Tecniche di supply chain;
- Progettazione e tecniche organizzative;
- Tecniche di management strategico.

Questa lista contiene ogni effetto che la modularizzazione può causare e che può essere utilizzato di nuovo in contesti diversi.

Limiti ed implicazioni per la ricerca

La modularizzazione è un concetto che dovrebbe includere la procedura di creazione di standard, che lo renderebbe uno strumento riutilizzabile ogni qualvolta un altro sistema voglia raggiungere delle condizioni di modularità.

Alcune caratteristiche di contesto non sono state considerate nella letteratura (probabilmente perché non sono tipiche del contesto manifatturiero, che è quello indagato principalmente in letteratura riguardo al tema della modularizzazione):

- L'aspetto meteorologico, che influenza la progettazione del sistema sociotecnico. Ad esempio, una centrale elettrica non verrebbe progettata allo stesso modo in un ambiente tropicale ed in un ambiente polare;
- L'aspetto geografico, che la letteratura menziona appena. Questa caratteristica di contesto porta alla valutazione di molteplici aree di competenza: la situazione politica, il contesto legislativo ed altre problematiche locali che potrebbero spingere a prendere determinate decisioni, che andrebbero ad interferire con il processo di modularizzazione;
- L'aspetto infrastrutturale, che svolge un ruolo di spicco nell'ambito decisionale della modularizzazione, specialmente durante la fase di sviluppo;
- Gli aspetti sociali vanno valutati con attenzione (ad es. La reperibilità di mano d'opera);
- ...

Solamente a seguito di un'approfondita valutazione del ciclo di vita, il decisore dovrebbe scegliere quale livello di modularizzazione sia più conveniente al suo caso. Questa problematica viene rappresentata dal tradeoff tra la convenienza di scomporre il sistema in parti piccole e maneggevoli e la generazione di un gran numero di interfacce.

Anche se la letteratura copre numerosi ambiti, il concetto non è stato completamente determinato. Sussistono dei domini (ad es. lungo il ciclo di vita oppure della supply chain) che ancora non hanno ricevuto l'attenzione dei ricercatori.

Inoltre, gli effetti della modularizzazione sono noti solo superficialmente: ogni decisione richiesta dalla modularizzazione porta ad una catena di eventi che impatta varie proprietà del sistema e di ciò che lo circonda.

Un limite al concetto di modularizzazione è rappresentato dalla superficialità della conoscenza dei meccanismi che governano le performance del sistema ed altri effetti. Ad esempio, le decisioni progettuali che impattano le diverse fasi del ciclo di vita di un sistema devono essere definite dopo un analisi approfondita delle fasi a valle di quella di progettazione (sviluppo, uso e dismissione). Ed è quindi sapendo quello che avviene dopo di essa che sarà possibile prendere la decisione più accurata.

Originalità/valore

Il concetto dovrebbe essere affrontato come decomposizione del sistema intero, mentre la maggior parte dei ricercatori lo definisce come essendo un processo di assemblaggio (l'argomento del clustering è ricorrente all'interno della letteratura).

L'introduzione della valutazione sistematica del concetto su vari fronti (ad es. ciclo di vita, supply chain, organizzazione dell'impresa, forza lavoro, conoscenza, ecc.) dà al concetto una nuova dimensione, che spinge verso l'applicazione di tecniche di modularizzazione migliorate.

Estratto in lingua italiana

I. Introduzione e ambito di impiego

Storicamente, la maggior parte degli articoli sul tema della modularizzazione disponibili in letteratura si sviluppano intorno al contesto della progettazione di prodotto (ad es. Langlois and Robertson, 1992; Ulrich, 1995; Garud and Kumaraswamy, 1995; Sanderson and Uzumeri, 1995). Essendo stato un tema ricco e approfondito, i ricercatori lo usarono come esempio per determinare quali fossero le problematiche incontrate ed i vantaggi riscontrati dall'applicazione di tale pratica. Il contesto in cui la modularizzazione è generalmente adoperata è caratterizzato da un prodotto altamente consolidato negli anni, che però richiede costantemente degli aggiornamenti (ad es. l'industria automobile in cui i modelli delle auto condividono componenti, o addirittura intere piattaforme, come descritto in Muffatto (1999).

Oggigiorno, una comunità crescente di ricercatori si è interessata alle applicazioni di questo concetto in altri ambiti, oltre a quello della progettazione di prodotto, come ad es. nella progettazione di impianti (Seifert et al., 2011), nella progettazione di organizzazioni (Sanchez e Mahoney, 1996), nella progettazione di servizi (Voss e Hsuan, 2009), ecc. Da allora, la definizione ricavata nel contesto della progettazione di prodotto è stata ampliata: il concetto che una volta era chiaramente definito, si è avverato essere antiquato ed inadeguato. Ci si può quindi domandare: quali sono le potenzialità ed i limiti di questo ampio concetto? Affinché si possa rispondere a questa domanda, conviene rimettere a nuovo le definizioni storiche del concetto, che già contengono gli aspetti più rilevanti.

La prima definizione fu data da Starr (1965), che disse che l'idea di base del concetto di modularizzazione stava nel "progettare, sviluppare, produrre [...] parti che possano essere combinate nel maggior numero di modi": questa definizione già allude alle diverse fasi che sono coinvolte nel processo di modularizzazione. Da allora, il concetto si è evoluto: negli ultimi 20 anni, molti ricercatori cercarono di mettersi d'accordo su quali fossero gli aspetti fondamentali della modularizzazione che permettessero di definire il concetto. La definizione più significativa fu data da Langlois (2000): la modularizzazione è un "insieme costituito da architettura, interfacce e standard". Altre definizioni più recenti (Mikkola, 2004; José and Tollenaere, 2005; Aurich et al., 2006; Seol et al., 2007; Rottke et al, 2012) si riferiscono alla modularizzazione come essendo la scomposizione/disgregazione di sistemi complessi/processi in sottosistemi/sotto processi più semplici/maneggevoli, con un'interfaccia ben definita, ma funzionando come un tutt'uno.

Prendendo come esempio la modularizzazione di un automobile, la sua configurazione deve cambiare, siccome certe parti che precedentemente erano considerate indipendenti sono ora sottosistemi di moduli. La decisione di come "effettuare il taglio" dell'automobile in moduli costringe in progettisti a considerare aspetti come la manutenzione dell'automobile durante il suo utilizzo, il riutilizzo dei moduli in altri prodotti, oppure addirittura il riutilizzo ed il riciclo, per quando il cliente desidererà cambiare automobile. Questi aspetti attirano l'attenzione su un elemento decisionale che le precedenti definizioni omettevano: la prospettiva di ciclo di vita.

Prescindendo dalle differenze che il campo di applicazione del concetto di modularizzazione prevede, questo esempio permette di scoprire una nuova dimensione: il concetto di modularizzazione deve essere generalizzato, affinché si possa definire una prospettiva di ciclo di vita che includa la valutazione di tradeoff che potrebbero influenzare la scelta seguente: vale la pena attuare la modularizzazione oppure no?

L'obiettivo di questo lavoro è la revisione della letteratura riguardo al concetto di modularità, con l'obiettivo di ridefinire il concetto di modularizzazione. Successivamente, è stato necessario porsi la domanda: "Perché si deve applicare la modularizzazione?" La risposta è stata cercata tramite l'arricchimento della definizione con l'ontologia strumentalizzata ai fini di concettualizzare la modularizzazione nei sistemi, con un enfasi particolare sulla prospettiva di ciclo di vita.

Questa tesi è costituita principalmente da 5 sezioni. La seconda sezione contiene la spiegazione della metodologia di ricerca, che è suddivisa tra la metodologia di raccolta degli articoli e la metodologia di revisione della letteratura: il lavoro è quindi riassunto in una base dati, usata successivamente per classificare (usando una tecnica di coding dell'informazione sulla modularizzazione) ed infine, per la ricerca delle informazioni all'interno degli articoli raccolti. Nella terza sezione viene data una descrizione generale dei dati raccolti ed alcuni dati statistici sono evidenziati. La quarta sezione è la parte centrale del lavoro: contiene la revisione dettagliata della letteratura divisa in quattro sottosezioni. Nella quinta sezione, si riassume l'ontologia della modularizzazione, che include una definizione del concetto, i confini, e le relazioni tra il concetto stesso, i fattori abilitanti e gli effetti. Infine nella sesta sezione, i risultati sono discussi, prendendo in considerazione i nuovi elementi introdotti precedentemente.

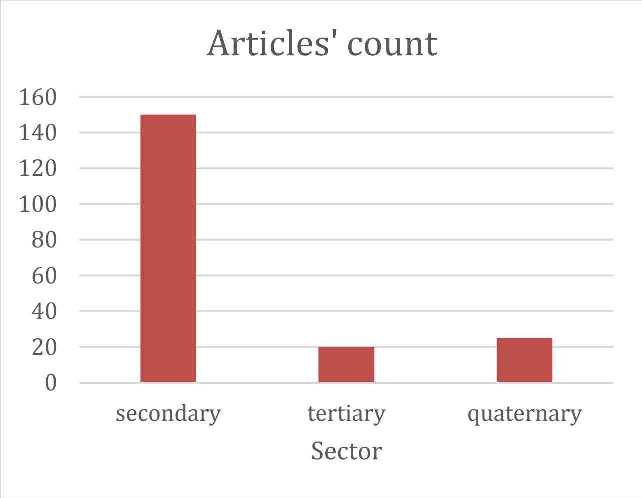
IV. Revisione della letteratura – 4. Questioni aperte

La revisione della letteratura porta a considerare alcune questioni non risolte riguardo al concetto di modularizzazione. Esse coinvolgono certi aspetti trattati durante la revisione della letteratura, ed alcune altre che provengono da considerazioni generiche. Il principale problema rimanente è legato alla domanda seguente: "dove va tagliato il sistema per realizzare la modularizzazione? E come va selezionato il taglio affinché si abbia la scomposizione migliore?" Questa questione è opposta alla ben nota tematica del clustering dei componenti in moduli (Lapp and Golay, 1997; Gershenson et al., 2004; Meehan et al., 2007; Tseng et al., 2008; Brandes et al., 2008), che è considerato un punto di riferimento della letteratura sulla modularizzazione. Considerare prima il sistema per intero ed in seguito, scomporlo in pezzi (Stone et al., 2000) non è una pratica abbastanza diffusa all'interno della comunità scientifica perché sia considerata un metodo di progettazione consistente.

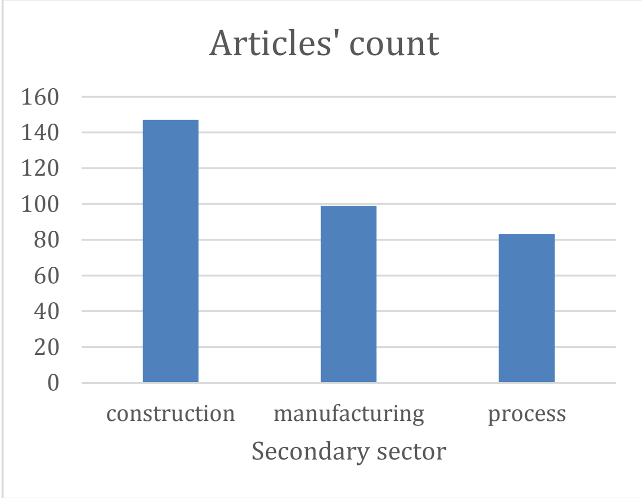
La scomposizione di un sistema in moduli obbliga l'impresa a definire un certo numero di interfacce ben specificate e standard. Questa decisione richiede un'attenzione particolare, siccome essa rappresenta una scelta progettuale importante e costosa, che interessa la maggior parte delle fasi a valle della progettazione, nel ciclo di vita del sistema. Il metodo più semplice per affrontare la questione è quello di considerare il tradeoff tre il numero di moduli portati ad interfacciarsi ed il livello di modularizzazione, ovvero quanto in profondità viene scomposto il sistema in sottosistemi, come è stato definito da Brusoni e Prencipe (2001). Questa tematica richiede un ulteriore approfondimento.

Un altro problema di prim'ordine riguarda la valutazione del ciclo di vita, argomento a cui le definizioni di modularizzazione non accennano, benché i ricercatori abbiano investigato in profondità le diverse fasi del ciclo di vita del sistema. Non si approfondisce la tematica riguardo alla catena di eventi che viene causata dal concetto, le quali conseguenze possono mettere a rischio la qualità, la funzionalità o addirittura la convenienza del sistema in forma modularizzata. Questa mancanza della letteratura scientifica non aiuta i professionisti ad applicare con sicurezza queste teorie in contesti pratici.

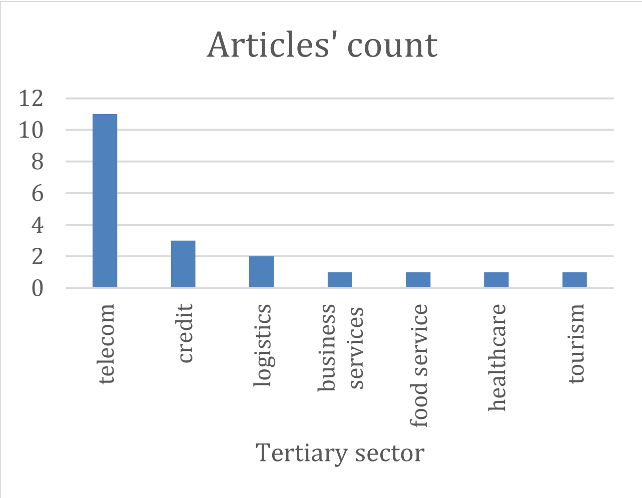
In seguito, si evidenzia la distribuzione delle pubblicazioni nei vari settori dell'economia: come viene mostrato nel Diag. 7, il settore dell'economia più studiato nella letteratura riguardo alla modularizzazione è il settore secondario. Il Diag. 8 evidenzia una copertura uniforme dei sotto settori del secondario, mentre il terziario (Diag. 9) ed il quaternario (Diag. 10) non sono stati studiati allo stesso modo del secondario che, come è stato accennato nell'introduzione, è stato il primo campo di ricerca investigato (principalmente per quello che riguarda il campo della progettazione di prodotto). Ciò dimostra che diversi settori dell'economia possono ancora essere l'oggetto di investigazioni da parte della comunità scientifica, prima che la modularizzazione possa essere considerata come un concetto definito universalmente.



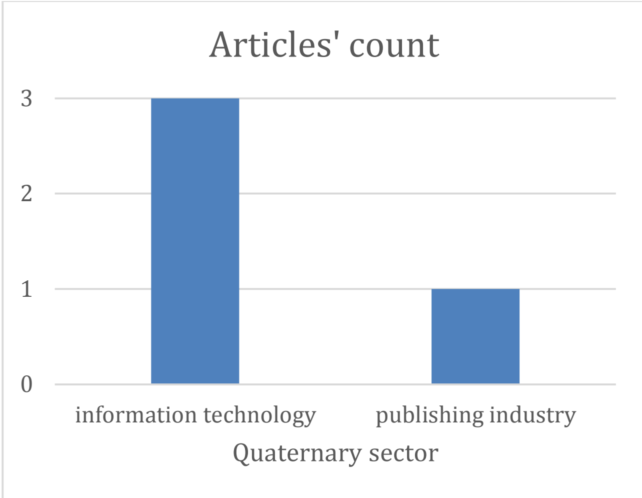
Diag. 7 Numero di articoli per settore



Diag. 8 Sotto settori del secondario



Diag. 9 Sotto settori del terziario



Diag. 10 Sotto settori del quaternario

La letteratura offre ai professionisti un certo numero di definizioni, che possono indurre in confusione il lettore: la maggior parte delle definizioni fornite dai ricercatori si riferiscono a contesti specifici che sono analizzati nei suddetti articoli. Ciò non è quel che i professionisti cercano quando decidono di rivolgersi alla comunità scientifica. Un primo interesse potrebbe riguardare una definizione universale del concetto, che aiuterebbe il generico decisore/manager a capire a cosa va incontro quando decide di adoperare tale tecnica.

In Tab. 39, le definizioni trovate in letteratura sono state revisionate in modo da evidenziare gli aspetti che restringono il loro campo di applicazione. Prendendo spunto dai seguenti aspetti critici, il prossimo capitolo contiene l'ontologia del concetto di modularizzazione.

	AUTORI	DEFINIZIONE	Aspetti critici
MODULARIZATION	Baldwin & Clark (1997)	A set of architecture, interfaces, and standards [...] Modularity is a strategy for organizing complex products and processes efficiently	- Nessun accenno al ciclo di vita.
	Gu & Sosale (1999)	Modularization allows modules to be produced, assembled and tested in convenient locations with equipment, tools and expertise	- Si perde l'aspetto strutturale della modularizzazione.
	Ernst & Kamrad (2000)	It implies a product design approach whereby the product is assembled from a set of standardized constituent units. Different assembly combinations from a given set of standardized units give rise to different end-product models and variations. […] It provides opportunities for exploiting economies of scope and scale from a product design perspective. […] Modularization essentially characterizes supplier responsibilities in terms of the outsourcing function.	- Nessun cenno alle caratteristiche delle interfacce. - Il prodotto viene considerate come un assemblaggio, ci si perde un aspetto essenziale della modularizzazione: "dove taglio?"
	Martin & Ishii (2002)	Fully modularized: the geometry, energy, material, or signal (GEMS) of the component can be changed to meet expected customer requirements without requiring other components to change. This implies that the CI–S (component index-supplying: indicates the strength (or impact) of the specifications that a component supplies to other components.) of the component is zero. Partially modularized: changes in the GEMS of the component may require changes in other components. The higher the CI–S, the more changes expected, and thus the component is considered less modular.	- Definizione parziale dell'estensione della modularizzazione. Non si riferisce né alla scomposizione del sistema, né agli standard.
	Mikkola & Skjott-Larsen (2004)	An approach for organizing complex products and processes efficiently by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. From a system's perspective, modularization can be perceived as a continuum outlining the degree to which a system's components can be decomposed and recombined. In other words, modularization 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	- L'utilizzo della parola "complex" riduce l'applicabilità della definizione. - Non si riferisce esplicitamente agli standard da adottare.
	Jose & Tollenaere (2005)	It is an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions. It allows the designer to play with combinations of groups of components to develop and customize a larger quantity of products.	- L'utilizzo della parola "complex" riduce l'applicabilità della definizione. - Non si riferisce esplicitamente agli standard da adottare. - Nessun cenno alle interfacce.
	EMWG (2005)	The process of converting the design and construction of a monolithic plant or stickbuilt scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies	- Ridotta al caso di impianti. - Trascura gli aspetti di interfaccia e di standard.
	Kotabe et al. (2007)	A strategic option that goes beyond the physical and functional dimensions of the module that includes an organizational and managerial system linking module integrators and module suppliers to reduce the cost of managing tacit knowledge in the assembly process	- Si riferisce unicamente ad aspetti legati alla supply chain.
	Rottke et al. (2012)	The basic idea is to break a complex system down into an assortment of easily manageable components with well-defined interconnections	- L'utilizzo della parola "complex" riduce l'applicabilità della definizione. - Nessun cenno agli standard.

Tab. 39 Definizioni di modularizzazione ed aspetti critici

VI. Discussione

Le definizioni fornite dai ricercatori sono state revisionate (sono riassunte in nel capitolo IV. 4.), ed ogni mancanza è stata evidenziata. L'obiettivo riguardante la generalizzazione del concetto è stato raggiunto tramite la costruzione dell'ontologia.

E però ancora necessario definire il legame tra modularizzazione e modularità. Miller e Elgard (1998) definiscono in modo soddisfacente il legame tre i due concetti:

"Modularità è un attributo del sistema che è relazionato alla struttura ed alla funzionalità. [...] Modularizzazione è l'attività durante la quale si strutturano i moduli."

Affinché si raggiungano le condizioni che permettano la modularizzazione, le proprietà di modularità devono essere definite dai progettisti: almeno un componente del sistema deve possedere delle caratteristiche di modularità affinché il processo possa essere chiamato modularizzazione. Quindi, la modularizzazione del sistema può essere convertita in una procedura standard, e quindi possa essere ripetuta in circostanze simili. In tal modo, il metodo può dar luogo a nuove espansioni modulari del sistema all'interno del suo ambiente.

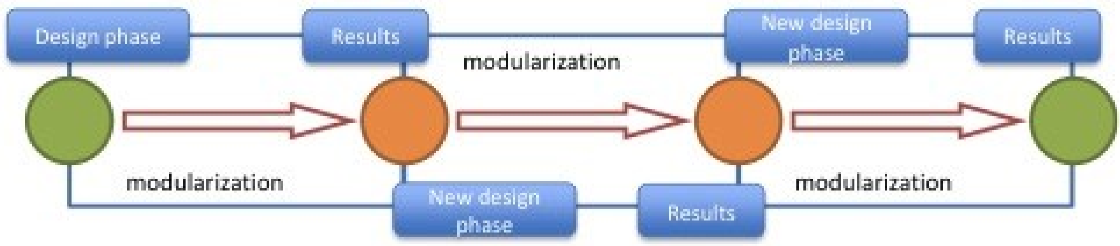


Fig. 8 Sequenza di modularizzazioni

Come mostrato nell'ontologia, il concetto può essere espresso come una scomposizione "dal alto verso il basso" del sistema intero, piuttosto che venga fatto un assemblaggio "dal basso verso l'alto" dei componenti in moduli. Un aspetto fondamentale della modularizzazione riguarda il fatto che il decisore deve essere libero di divide il sistema nel modo che lui ritiene migliore. Quindi, ha bisogno di conosce l'intero intreccio di possibili decomposizioni affinché gli sia possibile applicare il processo di modularizzazione per intero, che comprende la valutazione di qualsiasi fattore che interviene sul sistema modularizzato secondo vari criteri di lettura (ad es. il ciclo di vita in Umeda et al. (2009), la supply chain in Matos e Hall (2007), l'organizzazione dell'impresa in Hoetker (2006), la forza lavoro in Takeishi e Fujimoto (2001), la conoscenza in Brusoni e Prencipe (2001), etc.)

Questi criteri sono già descritti nella letteratura scientifica, ma rimangono frammentati per colpa del loro utilizzo mirato negli articoli dei ricercatori, che li utilizzano in specifiche aree di interesse. Questo esame, mentre la maggior parte degli attributi della modularizzazione può essere considerata esaustiva, va approfondito in certi contesti specifici che sono stati trascurati (probabilmente perché sono contesti lontani dall'industria manifatturiera):

- L'aspetto meteorologico, che influenza la progettazione del sistema socio-tecnico. Ad esempio, una centrale elettrica avrà caratteristiche diverse se l'ubicazione è tropicale oppure polare.
- L'aspetto geografico, che la letteratura menziona appena. Questa caratteristica di contesto interessa diverse aree di competenza: la situazione politica, il contest legislativo ed altri problemi locali che potrebbero richiedere la presa di determinate decisioni, che potrebbero interferire col processo di modularizzazione.
- L'aspetto infrastrutturale che interpreta un ruolo principale nelle decisioni riguardo alla modularizzazione, specialmente durante la fase di sviluppo.
- Bisogna tenere conto degli aspetti sociali (ad es. la reperibilità di mano d'opera)
- ...

Queste caratteristiche vengono dai problemi principali che i progettisti incontrano nel contesto dell'ingegneria di progetto (ad es. costruzione di impianti, organizzazione di eventi, edilizia, ecc.). La modularizzazione potrebbe risolvere i problemi legati a quelle caratteristiche.

Determinando il tradeoff tra la convenienza di spezzare il sistema in porzioni più piccole e maneggevoli (ad es. Mikkola e Gassmann, 2003) e la creazione di un elevato numero di interfacce (ad es. Gershenson et al., 2004) è ancora una questione non risolta (vedi Fig. 9), che però è troppo specifica nei casi singoli per potere fare parte di questa generica ontologia della modularizzazione.

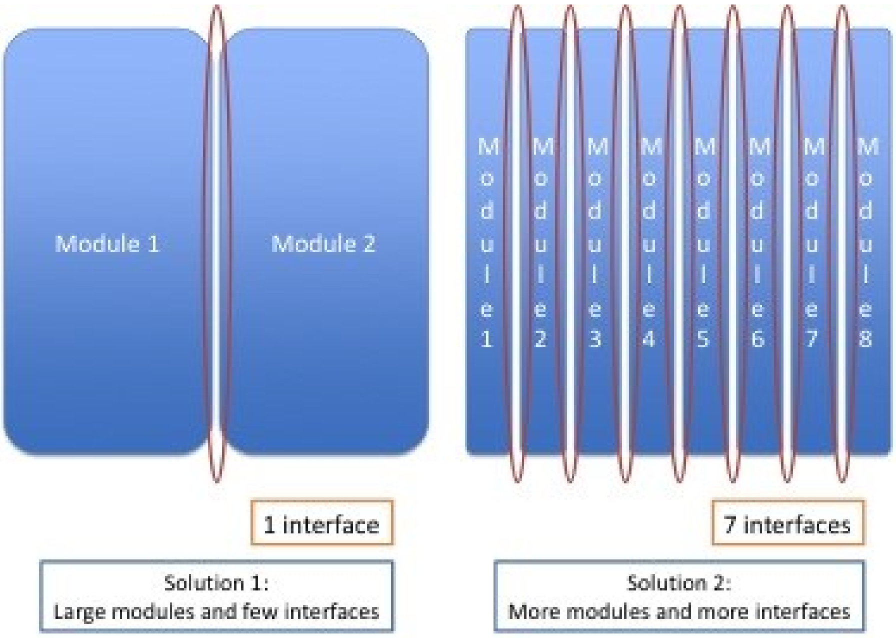
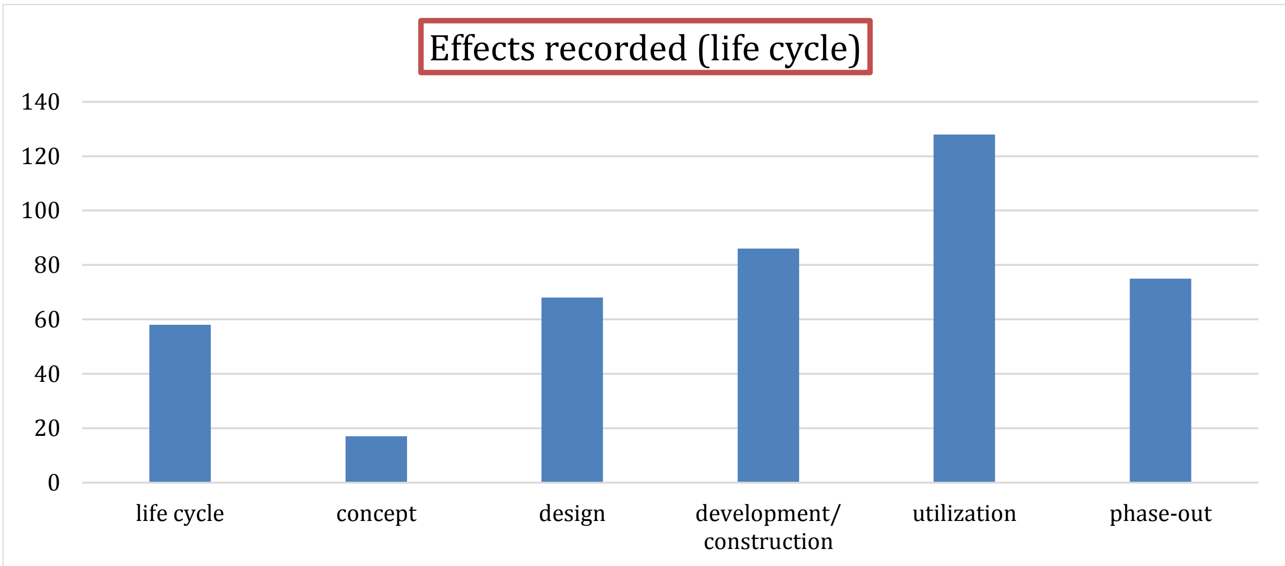


Fig. 9 La divisione del sistema in moduli

Storicamente, la decisione non dipende da valutazioni generali, come la valutazione del ciclo di vita, ma viene dalla valutazione degli aspetti legati alla fabbricazione/costruzione de prodotto fisico (che è tradizionalmente l'area di implementazione della modularizzazione). Ciò vale a dire che seguendo l'ordine di assemblaggio oppure la convenienza del processo di fabbricazione, il prodotto è messo insieme da diversi sottosistemi, senza minimamente considerare alcun aspetto legato al ciclo di vita, eccetto per gli aspetti riguardanti la fase di costruzione/produzione, che possono essere identificati genericamente dalla fase di sviluppo.

Il decisore dovrebbe valutare, considerando i criteri di lettura citati in precedenza (ciclo di vita, supply chain, organizzazione dell'impresa, mano d'opera, ecc.), quale sia il livello di modularizzazione che convenga di più nel suo caso. La decisione dovrebbe esser presa durante la fase concettuale, ovvero quando la maggior parte degli aspetti generali riguardo al sistema potenzialmente modularizzato sono ancora indefiniti.

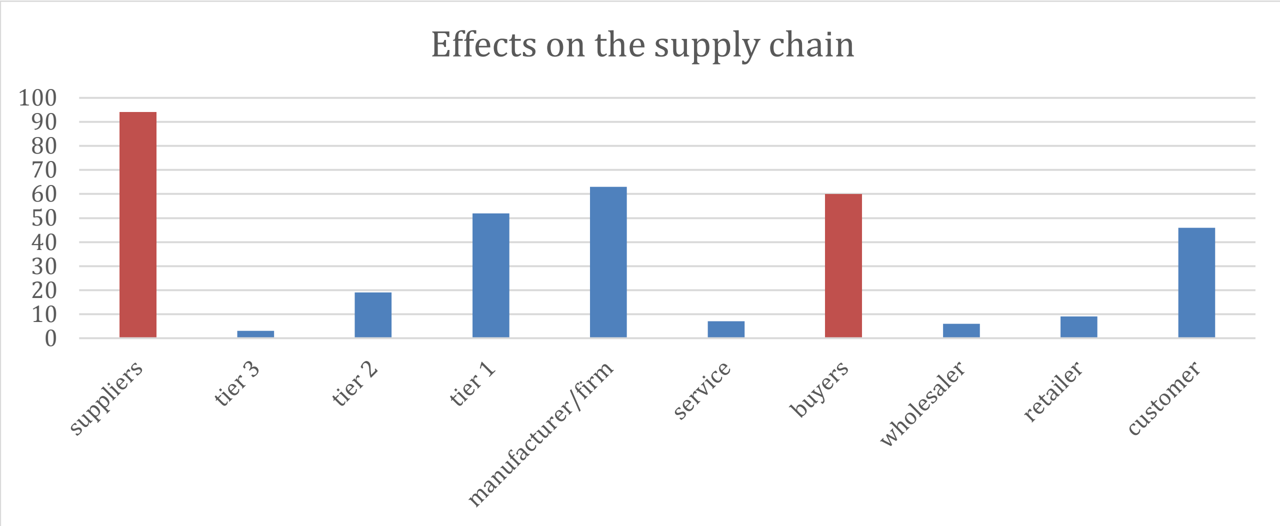
Nel Diag. 11, si osserva una particolare tendenza delle pubblicazioni, divise per effetti rilevati nelle varie fasi del ciclo di vita, che evidenzia chiaramente un interesse maggiore per quanto riguarda gli impatti della modularizzazione nella fase di utilizzo del sistema:



Diag. 11 Effetti rilevati durante le diverse faci del ciclo di vita

La modularizzazione può occupare una posizione di rilievo anche durante la fase di dismissione del sistema, permettendo di migliorare tecniche come il riutilizzo, la facilità del riciclo, ecc. Ciò porta ad una visione di ciclo di vita, che consiste nella valutazione delle caratteristiche di modularità (ovvero, delle proprietà interne al sistema, comandate dalla modularizzazione) e nell'impatto di esse su ogni fase del ciclo di vita del sistema.

Diag. 12 mostra quanti sono gli articoli che hanno effetto sulla supply chain. I fornitori sono citati più volte rispetto agli acquirenti, che sono principalmente identificati nella letteratura come clienti. Si può notare che la maggior parte degli articoli riguardanti gli effetti si interessano a fornitori di primo livello, al fabbricante/impresa ed ai clienti. Si nota però un interesse crescente per i fornitori di secondo livello (ad es. Fixson et al., 2005) che sono sempre più coinvolti nella modularizzazione, nella quale vengono date ai fornitori di primo livello responsabilità sempre più importanti.



Diag. 12 Effetti rilevati sulla supply chain

Al momento della decisione di modularizzare, è fondamentale capire quello che influenza il sistema modularizzato durante il ciclo di vita (Mehrabi et al., 2000). Ogni decisione porta ad un susseguirsi di eventi che impattano più aspetti delle proprietà di sistema ed elementi circondanti (ad es. Il cambio dell'interfaccia di un modulo impatta entrambi i moduli che sono connessi dalla suddetta interfaccia. Ma sono gli effetti limitati ai due moduli oppure tale cambiamento impatta anche altri elementi del sistema? Quali sono gli effetti sulle performance di sistema?)

Essendo la modularizzazione una decisione progettuale, si dovrebbe eseguire una valutazione completa del ciclo di vita affinché possano essere definite la maggior parte delle conseguenze dell'azione di modularizzare il sistema. Fig. 10 mostra come il concetto di modularizzazione sia descritto in letteratura e come invece dovrebbe essere visto il fenomeno:

- La valutazione di alcuni elementi (Fig. 10a) può portare ad una situazione in cui i progettisti, dopo aver attribuito alcune caratteristiche di modularità al sistema (che sono determinate da una analisi di superficie della catena degli effetti), si trovano faccia a faccia con problemi architetturali che richiedono di nuovo uno sforzo e risorse dall'impresa. Questi contrattempi sono principalmente dovuti alla mancanza di approfondimento dell'analisi.

- Invece, ogni effetto, effetto di second'ordine (e così via, come in Fig. 10b) dovrebbe essere investigato affinché si possa prevenire la maggior parte di eventi indesiderati. Ciò potrebbe addirittura dare l'opportunità di usare un grado maggiore di modularizzazione.

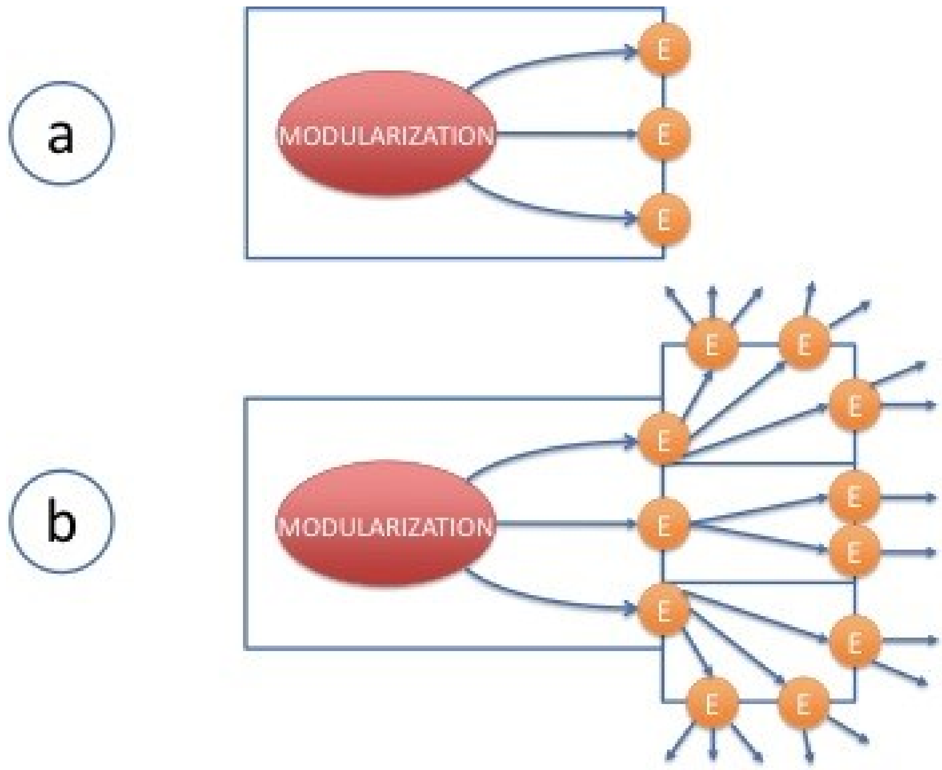


Fig. 10 Differenze tra (a) quello che è descritto dalla letteratura,
e (b) quello che dovrebbe succedere quando si usa la modularizzazione

Questo punto di vista permette di evidenziare che ogni modifica al sistema modularizzato spinge i moduli ed i sottosistemi verso dei cambiamenti che potrebbero compromettere l'ottimizzazione del sistema intero. Ad esempio, l'innovazione modulare (ad es. Galunic e Eisenhardt, 2001; Sosa et al., 2004) viene percepita come una fonte di competitività della modularizzazione, rispetto ad un sistema non modularizzato, ma queste alterazioni dei moduli potrebbero costringere i progettisti a riconsiderare l'intera architettura del sistema, a causa degli effetti che avrebbero potuto essere trascurati al momento della fase concettuale.

Il meccanismo della modularizzazione deve essere globalmente studiato, considerando la catena complessa di effetti concatenati, affinché sia possibile definire l'impatto complessivamente subito dal sistema e dall'impresa. Una volta che gli impatti sono noti, si può prendere una decisione riguardo a modularizzare oppure no. Ad esempio, le decisioni progettuali che hanno impatto sulle fasi del ciclo di vita del sistema (riquadro "Decision" in Fig. 11) devono essere determinate dopo aver praticato un'analisi dettagliata delle fasi a valle (sviluppo, utilizzo e dismissione), cioè del riquadro “Action” rappresentato in Fig. 11. Sapendo quindi quello che succede dopo che la decisione sia stata presa, si può prendere tale decisione più sapientemente.

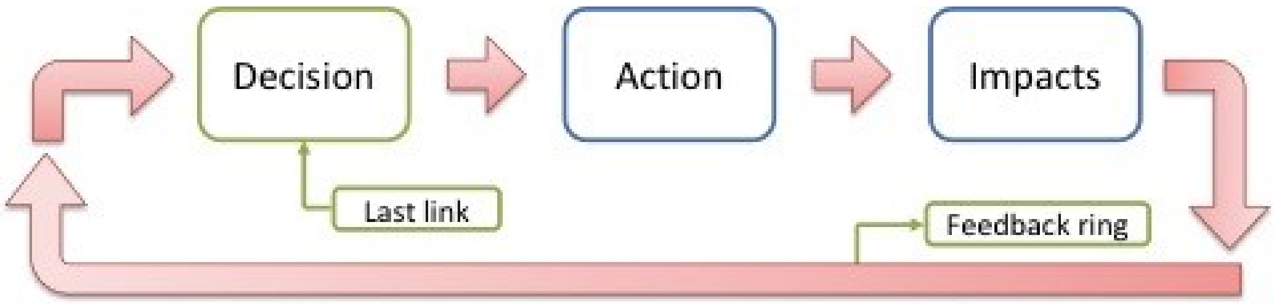


Fig. 11 Procedura decisionale generale riguardante qualsiasi fenomeno

La domanda fondamentale potrebbe a questo punto essere: perché un impresa deve impiegare la modularizzazione sui propri sistemi? Come è stato discusso nel capitolo IV. 3. b., i tipi di performance di cui una impresa potrebbe necessitare appartengono alle seguenti macro categorie:

- Economico
- Flessibilità
- Tempo
- Rischio
- Qualità
- Efficienza
- Varietà
- Customizzazione

Più la modularizzazione è utilizzata e più i progettisti si abituano ad avere a che fare con le conseguenze delle proprie scelte progettuali, e meno il sistema rischia di causare effetti negativi sull’impresa. La scomposizione in moduli di qualsiasi sistema richiede esperienza e conoscenza, che vengono acquisite esclusivamente quando la si usa.

Ricerche future

Come è stato evidenziato nelle questioni aperte della revisione della letteratura, alla domanda seguente deve ancora essere trovata una risposta: “dove taglio il sistema per compiere la modularizzazione? E come sarà scelto il taglio affinché si possa dire che questo è il modo migliore per scomporre il sistema?” Questa domanda ci porta alla valutazione di un tradeoff tra un sistema profondamente scomposto ed un sistema che possiede il minimo numero di interfacce.

Inoltre, la copertura dei settori dell’economia non è completa ed il progresso ottenuto nel dominio dei prodotti fisici deve essere trasmesso ed approfondito in numerosi settori non coperti (ci sono numerosi esempi nei settori terziario e quaternario). Gli studi approfonditi che sono stati eseguiti nell’ambito dei prodotti fisici devono essere usati come base investigativa per valutare gli effetti della modularizzazione, ad esempio sugli oggetti intangibili e sui manufatti non assemblati. Allo stesso tempo, la conoscenza riguardo alle caratteristiche dei contesti elencate durante la discussione devono essere maggiormente approfondite.

Dall’ontologia che è stata sviluppata (ovvero la nuova ed espansa definizione del concetto, le sue frontiere ed i suoi fattori abilitanti ed effetti all’interno di un contesto definito), i ricercatori possono investigare i meccanismi della modularizzazione (cioè la catena di eventi che l’azione di modularizzare scatena), le cause e gli effetti di ogni singola conseguenza che la modularizzazione determina: ogni aspetto descritto nel capitolo IV. 3. b. deve essere stimato ed i fattori di mediazione devono essere investigati (alcuni effetti rilevati durante la revisione della letteratura sono in contradizione, questa incoerenza deve essere chiarita).

I. Introduction and scope of work

Historically, most of the research papers available in scientific literature upon the modularization theme were developed inside the context of product design (e.g. Langlois and Robertson, 1992; Ulrich, 1995; Garud and Kumaraswamy, 1995; Sanderson and Uzumeri, 1995). It has been a really rich and covered path that the academics used as a background to determine which issues are encountered and which advantages are obtained from this practice. The context where modularization generally takes place is characterized by a highly consolidated product over the years, which however needs frequent upgrades (e.g. automobile industry in which car model share components or even entire platforms, like in Muffatto (1999)).

Nowadays, an enlarged community of researchers observe that the concept is applied in different scopes beyond product design, e.g. in plant design (Seifert et al., 2011), in organization design (Sanchez and Mahoney, 1996), in services design (Voss and Hsuan, 2009), etc. Since then, the definition that was obtained in the product design context gained a larger meaning: the concept that was once clearly defined turned out to be outdated and inadequate. Consequently, one can ask: which are the potentialities and the limits of this broad concept? To investigate these issues, it is convenient to revive the historical definitions of the concept, which already contained the most relevant aspects.

The first definition introduced by Starr (1965) was sentencing that the idea behind modularization is to "design, develop, produce […] parts which can be combined in the maximum number of ways": this definition already mentions the different phases that are involved by the modularization process. Since then, the concept evolved: in the past 20 years, many researchers worked on trying to reach a consensus on which fundamental aspects of modularization define the concept itself.

The most significative definition was given by Langlois (2000): modularization is a "set of architecture, interfaces, and standards". Other more recent definitions (Mikkola, 2004; José and Tollenaere, 2005; Aurich et al., 2006; Seol et al., 2007; Rottke et al, 2012) refer to modularization as the decomposition/breakdown of complex systems/processes into more simpler/manageable subsystems/sub processes, with well-defined interfaces, but operating as a whole.

Considering the modularization of an automobile, its configuration has to change, since some of the parts that were previously considered as stand-alone are now subsystems of modules. The decision of how to "cut" the automobile into modules obligates designers to consider aspects like maintenance of the automobile during its utilization, modules reuse in other different products, directions for the innovation of the modules, or even reusing and recycling when the customer wants to change his automobile. Those aspects draw attention to one decisional element that previous definitions omit: the life cycle perspective.

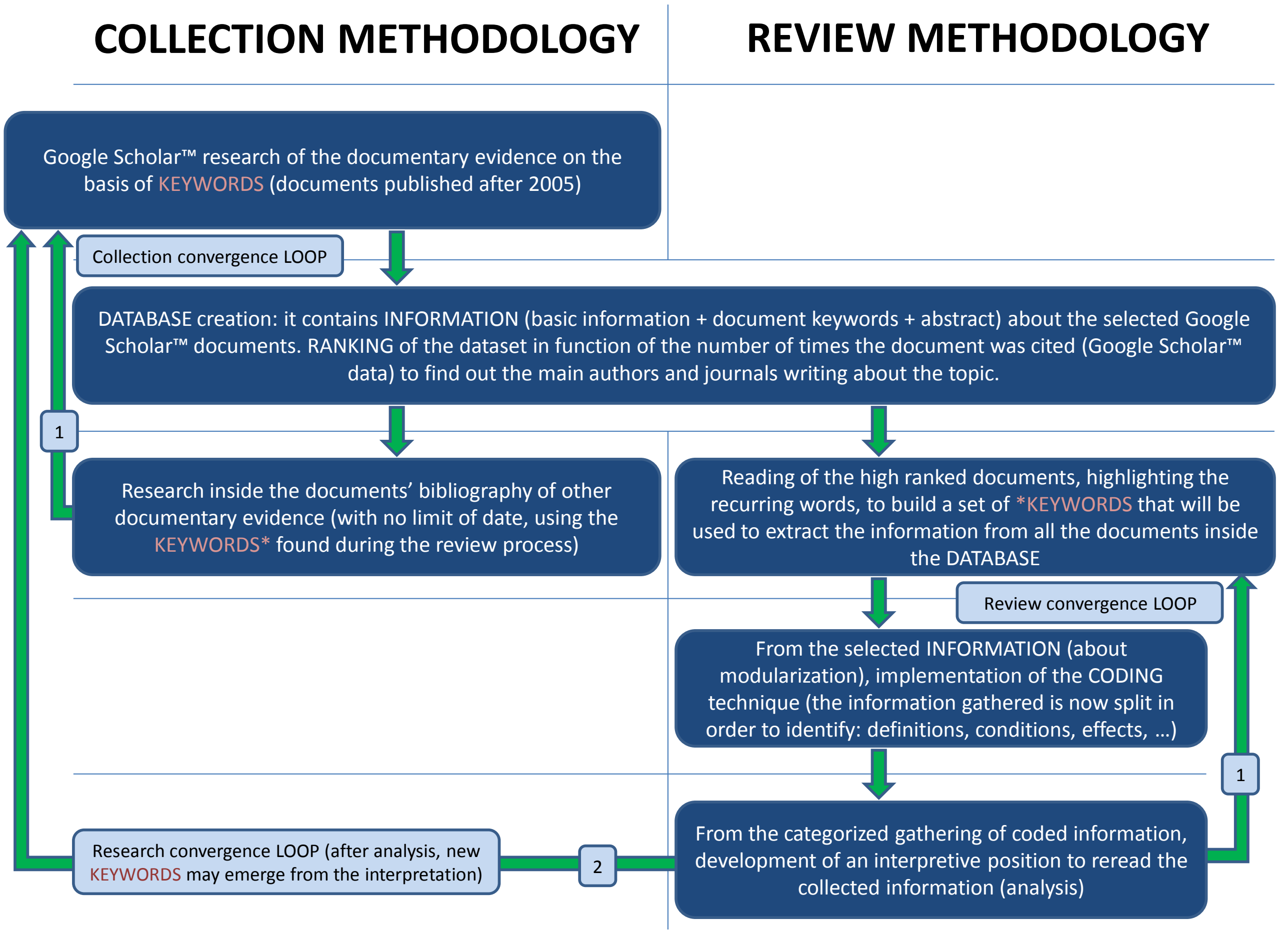
Regardless of the differentiation among the field of application of the concept of modularization, this example opens to a whole new dimension: the modularization concept has to be enlarged to assume a life cycle perspective, including trade-off decisions that may influence whether adopt modularization or not.

The aim of this work is to review the literature upon the "modular concept" with the objective of redefining the concept of modularization. After that, it is necessary to ask the question: "Why should modularization be adopted"? That is why the definition had to be enriched with the literature-grounded ontology about the conceptualization of the modularization of socio-technical systems with a particular emphasis upon the life cycle perspective.

This thesis is structured in 5 main sections. Section 2 explains the research methodology, including the literature collection methodology and how is has been reviewed: the work is summarized in a database that has been used to classify (using a coding technique of the information upon modularization) and later, to retrieve the information gathered from the collected papers. Section 3 provides a general description of the data collected, and some statistical data is presented. Section 4 is the body of the work, and contains the details of the reviewed literature divided in four sub-sections. In section 5, a literature-grounded ontology of the modularization is formulated; it includes a definition of the concept, the concept's boundaries, and the relationships between the concept itself, the enabling factors, and the effects. Finally in section 6, the literature is discussed considering the new elements introduced in Section 5.

II. Research methodology

The research methodology is composed by two distinct parts: the data collection methodology and the review methodology. Those two processes are represented in the following Tab. 1:



Tab. 1 Research methodology

1. Data collection methodology

The first step consists in an internet research with a research engine: two of them were taken into account: Google Scholar™ and SciVerse Scopus™. The first one is a very generic bibliographic database that links the researchers to most of the peer-reviewed online journals, books and non-peer reviewed journals. The second one is a bibliographic database that links only to the peer-reviewed online journals, therefore giving a narrower vision of the most recent literature, which has not had yet the opportunity of being reviewed.

Google Scholar™ was preferred to SciVerse Scopus™ because of its wider research results overview, in order not to miss any information, even the one which has not been peer-reviewed yet. The articles selected belong to the engineering or management themes. Other topics (like computer science, chemistry or social science) have been excluded regardless of their contents.

To have the most valuable collection of information, two essential principles were applied all along the process:

- Mutual exclusion, to be sure that every information should have only one category label and so, no overlapping with other information,
- Exhaustiveness, to guarantee the most complete work frame.

The following research keywords were investigated on Google Scholar™:

- Modularization,
- Plant modularization,
- Modular plant,
- Life cycle modularization
- Industrial plant
- Modular
- Modularity

The research started from the keyword "Modularization", because it is the concept this work is all about. By storing the papers inside a database, the collection shaped up into a detailed list of contents, where every aspect of the paper considered relevant for the research was indexed:

- The general information about the paper (title, year of publication, authors, …),
- The abstract of the paper,
- The number of times it is cited (the data was taken from Google Scholar™ at the moment of the research),
- The paper's official keywords (when the paper had no official keywords, Scopus™ automatic keywords were used).

Some more specific keywords were added to direct the research towards the scope of the research project this work started from (available upon request). "Life cycle modularization" was necessary to explore a new characteristic of the concept that the current collection was driving toward. Finally, "Modular" and "Modularity" were added to track down the papers what weren't indexed under "Modularization" (most of the papers found out using "Modularization" as a keyword were referring to the concept of modularity). Moreover, the papers cited in the research document were included in the collection.

2. Review methodology

Initially, the review of the literature was supposed to start with the creation of a list of research keywords, which would have been used inside the papers to locate the relevant contents about modularization. The research keywords are the following:

- Reuse,
- Prefabrication,
- Preassembly,
- Product,
- Family,
- Platform,
- Module,
- Bundle,
- Decomposable,
- System.

Every time that a new research keyword would be added to this list, previously "unpacked" papers would be inspected again, in order to check that the information is as complete as possible. Finally, to speed up the gathering of the information, another strategy has been used: the papers have been browsed using the prefix "modul-" (that allows to find the words "module(s)", "modular", "modularity", "modularize", "modularized", "modularization", "modularisation", "remodularization") in the "find function" of the PDF reader, to highlight modularization contents only. Every time a relevant set of words was identified anywhere near a sentence about modularization, it was included in the database, which is subcategorized as it follows: Modularization definition related concepts, Pre-conditions, Enabling factors, Critical factors, Limits, Advantages, Advancement/Innovational aspects, Application fields, Actors involved, Timeline. These subcategories were then useful to divide every aspect of the ontology by typology of content about the modularization concept, which speeded up the general synthesis of the gathered information.

In order to make this database exploitable, a technique of information coding has been used to categorize the articles' information into a well-defined framework.

First, a standard scheme was developed upon the 6Ws questions (Who, What, When, Where, Why and Which way). This system was supposed to guarantee the completeness of the decomposition at every sub-level (being every sub-level a rational decomposition of the superior level, the information was supposedly categorized in the most complete and logic tree), but this technique has been only partially implemented, because of the complications encountered: the categories of the decomposition tree were getting more and more detailed, leading to an tool that would have been impossible to manage. A sample of the decomposition tree (1st level) is represented in Tab. 2:

WHO	WHAT	WHEN	WHERE	WHY	HOW
Firm	Architecture	Conception phase	Product	Economical issue	Skills/Expertise
Suppliers	Tools	Feasibility phase	Program	Innovation	Standards/ Commonality
Customers	System	Contracting phase	Portfolio	Quality	Methods
Competitors	Design	Design phase	Process	Service	Specifications
Partners	Knowledge	Development phase	Service	Risks issue	Improvements
Distribution	Flows	Procurement phase	Factory	Flexibility1	Substitutions
Contractors	Information	Fabrication phase	Internal/ External	Variety	Flexibility2
Stakeholders	Resources	Utilization phase	Scope of work		Organization
Researchers	Structures	Dismission phase			Break down
	Interactions	Life cycle			Time issue

Tab. 2 Sample of the 6Ws' decomposition tree

In the end, the coding scheme suggested by Strauss and Corbin (1990), which has been used to develop grounded theory upon qualitative research, has been adopted to create a framework that would allow to analyze the data gathered. It is made of three steps:

- The first step is OPEN CODING: "The analytic process through which concepts are identified and their properties and dimensions are discovered in data". In our case, a process of synthesis has been used on the most relevant keywords that emerged from the papers, to categorize them a set of less specific characteristics. Those characteristics were the starting point to formulate a framework for the keywords
- The second step is AXIAL CODING: "The process of relating categories to their subcategories, termed 'axial' because coding occurs around the axis of a category, linking

categories at the level of properties and dimensions". Then as the first categories were emerging, a hierarchical order was given to the characteristics, in order to transform the data summarized into a well-defined framework.

- The third step is SELECTIVE CODING: "The process of integrating and refining the theory. The point in category development in which no properties, dimensions, or relationships emerge during analysis". In this step, the framework formulated has been filled with the generic keywords that were picked from the literature. As all the individual keywords were categorized into the coding scheme, the database was being completed.

According to that coding scheme, the information has been re-systematized by using a decomposition of every framework's synthetic concept following a defined rational hierarchy: this hierarchical decomposition of the concepts follows a bottom-up logic, therefore the formalized categories (as described in the scheme suggested previously) arise from a synthesis of the literature's keywords. To illustrate the method, the scheme of the decomposition tree is reported in Fig. 1 (for a matter of clarity, only the first three levels are represented)

The literature is then reviewed, capitalizing on the sub-categorization of the database and the definition of the coding's framework, to highlight the aspects of modularization that could help to shape an ontology of the concept. Therefore, the most interesting features regarding the definition of modularization, its boundaries, and its relations with enabling factors and effects will be brought up to understand what the whole modularization is meaning.

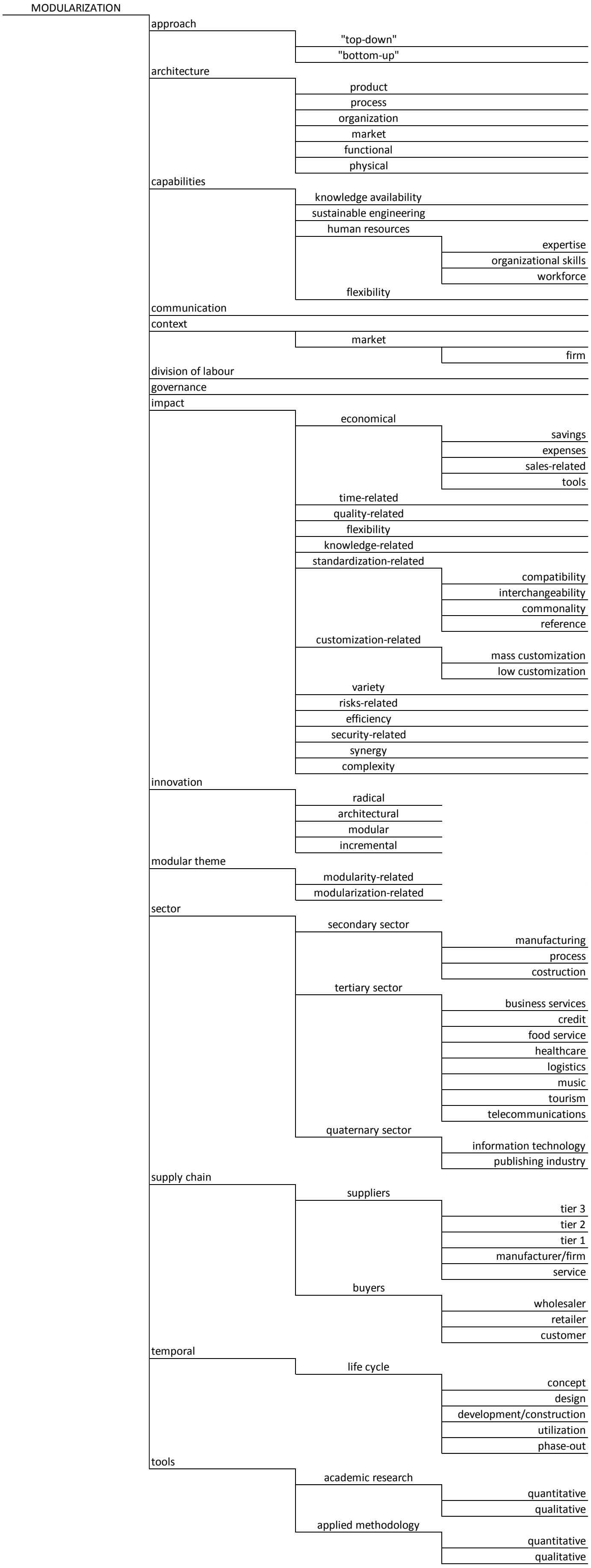
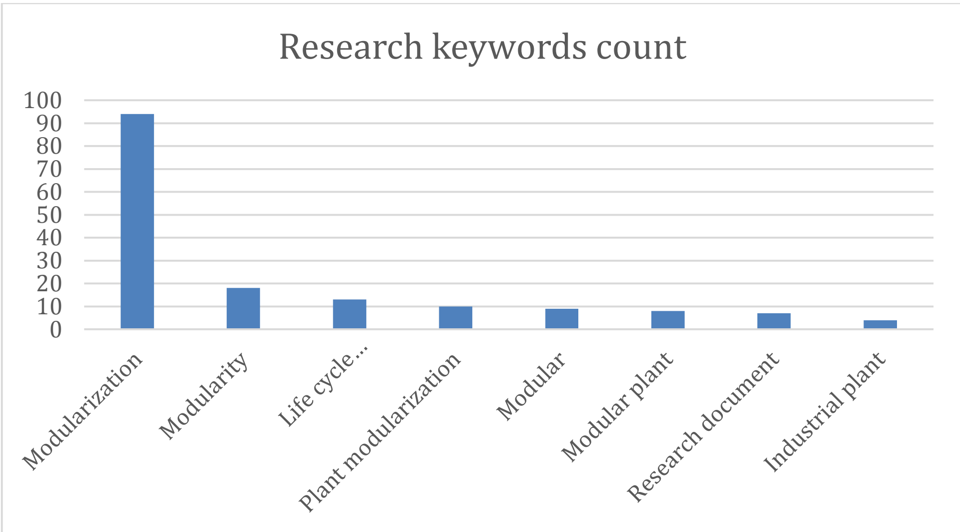


Fig. 1 Framework

III. Literature collection

The research made on Google Scholar™ resulted in a collection of 160 papers obtained following the collection methodology illustrated in the previous section.

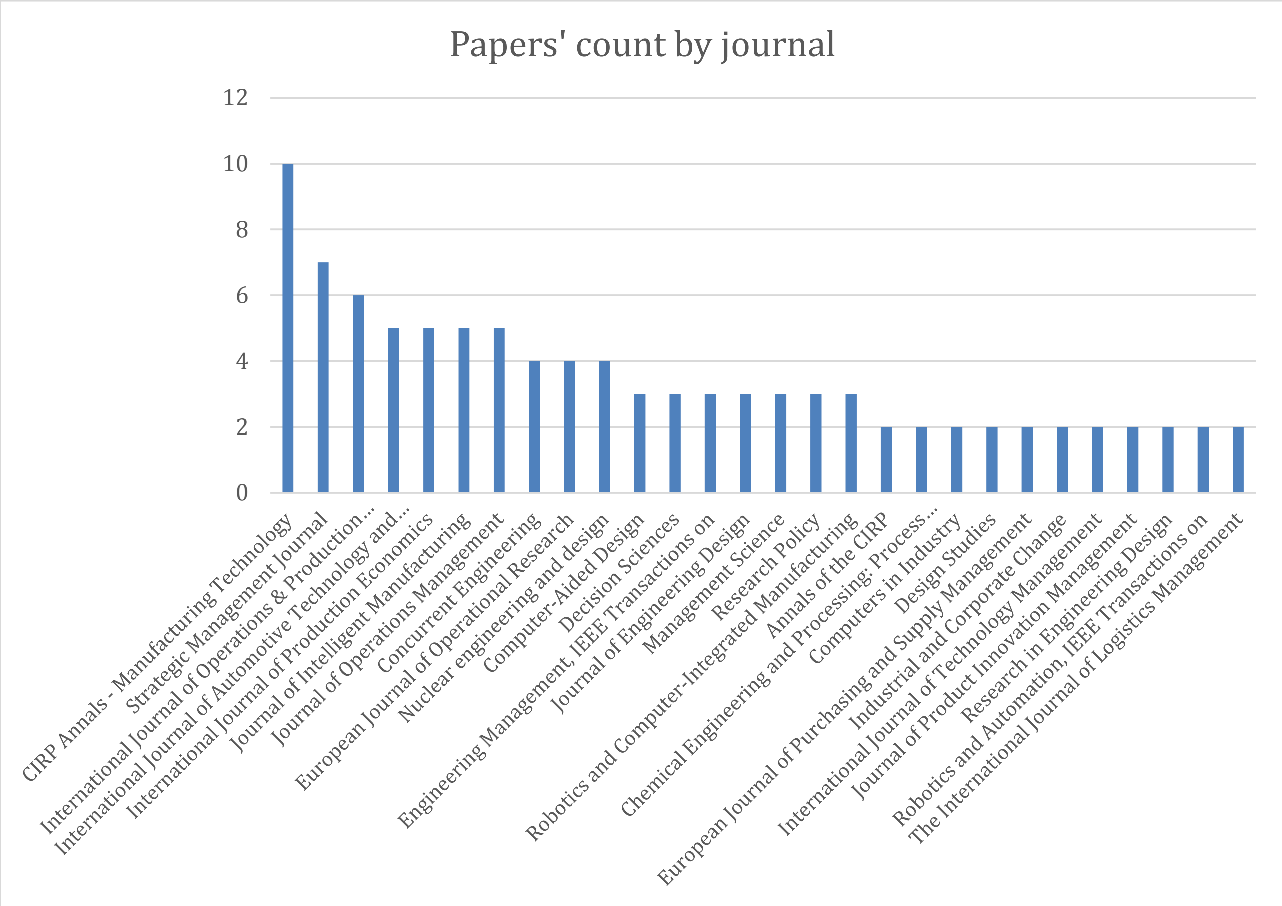
Then, from the results found under those research criteria, another filter has been applied, excluding from the results the papers that weren't concerning directly the modular issue or the industrial or managerial contexts. Most of the relevant papers were obtained from the first keyword, as it is shown in Diag. 1. This anomaly is caused by the fact that the papers already found and collected under the "modularization" keyword weren't counted again when they were appearing within the other keywords' research results. Moreover, the papers found from the bibliography of other papers were included under the same research keyword.



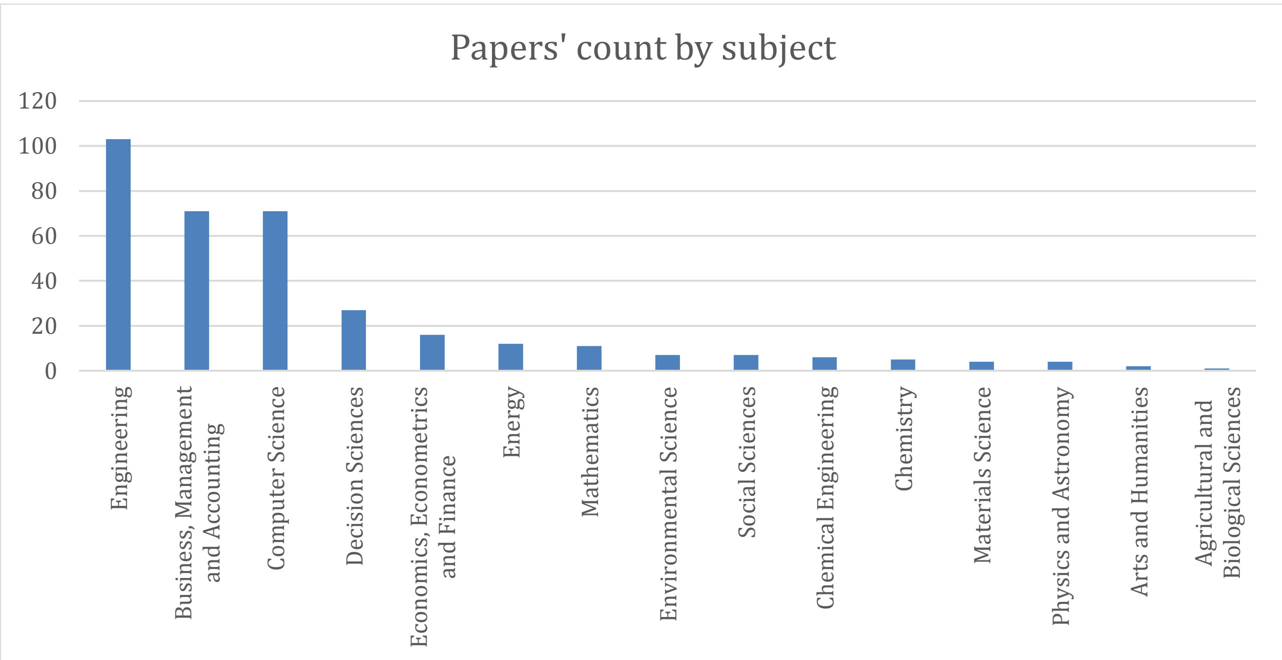
Diag. 1 Articles found by research keyword

The journals which published more than one paper about the modularization theme are listed in Diag. 2, whereas the complete list can be found in Appendix A. In Diag. 3, all the papers' subjects have been identified from SciVerse Scopus journals' database: it shows that most of the papers about the modularization concept include basically 5 main macro-subjects:

- Engineering
- Business, Mgmt, and Accounting
- Computer Science
- Decision Sciences
- Economics, Econometrics, and Finance

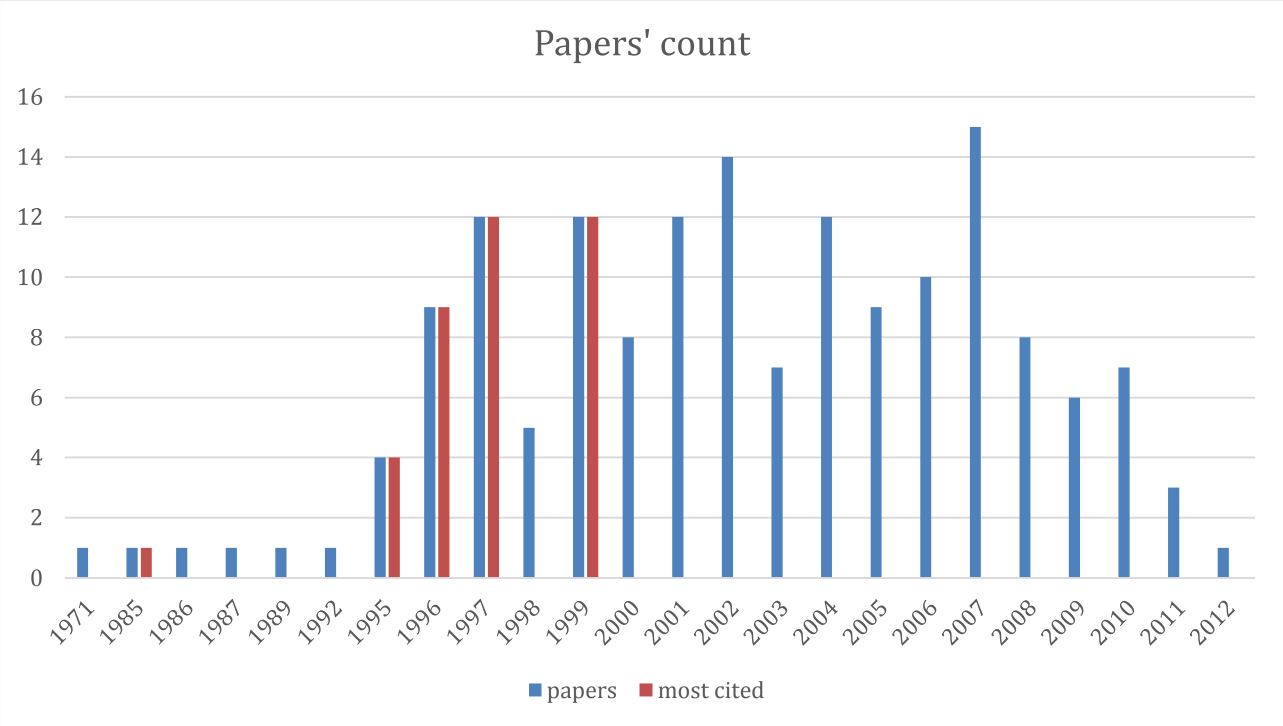


Diag. 2 Papers collected, by journal



Diag. 3 Papers collected, by subject (taken from SciVerse Scopus™)

In Diag. 4, the chronology of the scientific research upon modularization draws attention to the growing interest of the practitioners from 1995. Since then, the average number of publications selected from the literature upon the modularization theme reached a relevant level (eight publication per year). Furthermore, the years when most cited articles have been wrote, are represented (in red) on the histogram: this information indicates that the work considered the most by the researchers is concentrated at the beginning of the "fever for modularization" era.



Diag. 4 Articles found by publication year

Another phenomenon that can be noticed is the one connected to the decrease of the number of publications in the last years. This means that the literature that describes the modularization is ripe. This permits to investigate the topic under all the points of view that have been considered worth being studied. As a matter of fact, the aim of this work is to write an ontology of the concept.

IV. Review of the literature

The information collected has been extracted from every paper by selecting a short combination of words as a description. The objective of this procedure was to gather the information without having to review again the papers already analyzed. However at this point, the gathered information needed to be uniformed: every synthetic concept, pulled out from its context was meaningless, so the previously explained technique of coding has been employed to give to every combination of coded words the most meaningful and descriptive dimension.

1. The definition of modularization in the literature

The modularization is arousing a growing interest within the scientific community. This concept was introduced in the literature by Starr (1965). Since then, many researchers tried to define the concept and to apply it to their domain of competence.

Baldwin & Clark (1997) sum up by affirming that modularization is *"a set of architecture, interfaces, and standards"*. This means that these three characteristics must be defined in a certain manner, so that the so-defined system can be considered as a result of the modularization process. This involves only design decisions that may restrict the range of the concept of modularization which involves other dimensions. They also declare: *"Modularity is a strategy for organizing complex products and processes efficiently"*. This information underlines the importance of the good management upon the design function, which may be overseen in many different ways (e.g. global management, local management ...)

Gu & Sosale (1999), in their paper upon product modularization for life cycle engineering, state that *"modularization allows modules to be produced, assembled and tested in convenient locations with equipment, tools and expertise."* This point of view involves interesting aspects of the concept, like the impact of modularization design decisions on downstream phases of a product life cycle, and the influence of the geographical issue upon the availability of resources/assets.

Ernst & Kamrad (2000) link the concept of modularization to standardization, by telling that *"it implies a product design approach whereby the product is assembled from a set of standardized constituent units. Different assembly combinations from a given set of standardized units give rise to different end-product models and variations. [...] It provides opportunities for exploiting economies of scope and scale from a product design perspective. [...] Modularization* *essentially characterizes supplier responsibilities in terms of the outsourcing function."* In the second and third part that have been transcribed, one can notice the effect of modularization on production: not only can modularization activate virtuous mechanisms, but it also gives the opportunity to improve the product's supply chain.

Martin & Ishii (2002) introduce in the modularization concept, the idea of differences between different levels of modularization; namely, they introduce two different definitions, referred to the design phase:

- *"Fully modularized: the geometry, energy, material, or signal (GEMS) of the component can be changed to meet expected customer requirements without requiring other components to change. This implies that the CI–S (component index-supplying: indicates the strength (or impact) of the specifications that a component supplies to other components.) of the component is zero."*
- *"Partially modularized: changes in the GEMS of the component may require changes in other components. The higher the CI–S, the more changes expected, and thus the component is considered less modular."*

This distinction shows how much module independence influences the most essential product features. The first definition emphasizes the way modularization enables local product design flexibility (the component's essential characteristics may vary without needing any change from the system's point of view).

Mikkola and Skjott-Larsen (2004) gave the following definition of modularization*: "an approach for organizing complex products and processes efficiently by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. From a system's perspective, modularization can be perceived as a continuum outlining the degree to which a system's components can be decomposed and recombined. In other words, modularization 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"*. This definition is pointing out the fact that modularization makes sense only for complex systems, which may be shutting the horizon of possible simple scenarios. The interesting part is regarding the word "continuum", which implies the diffusion of the concept of modularization across the system's life cycle, highlighting the way this concept is influencing a series of aspects and contexts that are scattered on a long time period. Then finally they summarize by alluding to the interfaces and the architectural rules that enable mixing and matching of components. In this case, one can interpret the word "component" in its more general meaning, which may refer to anything that is part of a larger system.

Jose and Tollenaere (2005) define modularization as "*an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions. It allows the designer to play with combinations of groups of components to develop and customize a larger quantity of products"*. This reinterpretation of the previous definition within the context of designs and complex operations makes the concept of customization shine through this new definition. It also touches on the multiple combinations the modularization enables to create.

During the EMWG-Economic modeling working group (2005), modularization like is defined as *"the process of converting the design and construction of a monolithic plant or stickbuilt scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies"*. This definition refers exclusively to the Engineering and Contracting world, overlooking every other context where modularization could be employed. Anyway, this definition gives an outlook on an important point of the concept characteristics: it mentions that transportation and assembly may be a lot easier if preassembly was taken into account during the system's design stage. The scope of this statement could be enlarged to other contexts, where the spread of physical products needs particular promptness (e.g. perishable goods).

Kotabe et al. (2007) state that modularization is *"a strategic option that goes beyond the physical and functional dimensions of the module that includes an organizational and managerial system linking module integrators and module suppliers to reduce the cost of managing tacit knowledge in the assembly process"*. The outstanding concept from this definition is the involvement of the entire supply chain in the modularization process, which plays a major role in the development of a successful modularized system.

Finally, Rottke et al. (2012) published the following definition: *"The basic idea is to break a complex system down into an assortment of easily manageable components with well-defined interconnections"*. They highlighted the main concept that modularization is about, that is to say the system's breakdown, which arises from a decision making process that involves many parameters.

However, most of the literature about modularization is built around the concept of modularity, which can be identified as one of the main objectives of the modularization configuration. Historically, it has been the term used by the practitioners to describe the phenomenon, way before they started to consider it through time.

The word "modularity" played a major part in the history of the concept's definition: researchers started analyzing the fait accompli rather than defining the complete concept; that is to say the modularization description was made necessary when the scientific community needed to understand the complete context where modularity was designed, applied, and experienced.

As it was said before, Starr (1965) was the first to describe the concept, he affirms that the main purpose is to *". . . design, develop, and produce . . . parts which can be combined in the maximum number of ways"*. This definition entails that the concept, as broad as it is, can be applied to every step of the life of any kind of object. Hereafter, the concept has also been applied to immaterial systems, obligating the practitioners to modify the historical definition.

In the same context as Starr, Walz (1980) argues that a modularized object is *"constructed of standardized units of dimensions for flexibility and Variety in use"*. In this sense, the concept of standardization is introduced, giving to the definition of modularity a new dimension: not only the modularity requires specific interfaces characteristics, but also to define standards within the subsystems.

Another definition, referred to physical objects, is suggesting that modularity is *"(1) Similarity between the physical and functional architecture of the design and (2) Minimization of incidental interactions between physical components"* (Ulrich & Tung, 1991). In the same manner, Chan et al. (1994) are arguing that modularity is based upon the *"relationship between achieving functional independence and reducing the interactions between modules"*. (Chen et al., 1994) which is in part what Ulrich & Tung were proposing. The authors introduce the issue connected to how the components fit well together, which means that modularity requires a particular architecture and specific interface features.

As Sanchez & Mahoney (1996) stated, modularity is a *“special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications“.* This definition also insists on the importance of the design phase, talking of interface definition and specification.

Baldwin and Clark (1997) define the successful way to apply modularity to computer industry, it is the *“building of complex product or process from smaller subsystems that can be designed independently yet function together as a whole”*. However, this definition might be valid also for other domains, depending on how the expressions “complex product” and “subsystem” are defined. The authors a still referring only to the design phase.

For Huang & Kusiak (1998), modularity is *“the use of common units to create product variants. It aims at the identification of independent, standardized, or interchangeable units to satisfy a variety of functions.”* Here again, the definition is very broad, and may be used in many contexts. But in this case, the authors underline the fact that modularity arises from the use of common units. Commonality is so introduced as a fundamental characteristic of the concept, which is allowed by the standardization.

Schilling (2000) gave the following extended definition: “*Modularity is a general systems concept: it 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. […]At its most abstract level, it refers simply to the degree to which a system's components can be separated and recombined. Since all systems are characterized by some degree of coupling (whether loose or tight) between their components and very few systems have components that are completely inseparable and nonrecombinable, almost all systems are, to some degree, modular.*” This generalization is very important, because it means that in every field of business, there is a system with characteristics that may change to match the requirements of modularization and in this way, enjoy the benefits of being modular. Even if this definition opens to a whole new dimension, it confines the concept to the coupling and the separation/recombination, excluding other perspectives.

As many firms develop their competitive advantages around the concept of modularity, and they are advertising to the customers the benefits they might obtain from the modular side of their product, the modularity is obviously a reason the marketing department might take advantage of (Brusoni & Prencipe, 2001).

Brusoni & Prencipe (2001) observed that *"the concept of modularity itself, as put forward in the current literature, is ex definitione static."* This statement draws the attention on an important issue of today's definition of modularity, that is to say the inability of the researchers to expand the range of the concept to the complete system's life cycle: not only the modularity has to be designed, but it is essential to include the development and the effects of it within the definition of the concept itself.

Langlois (2002) states that modularity *"is a general set of design principles for managing the complexity of such large-scale interdependent systems. It involves breaking up the system into discrete chunks that communicate with each other through standardized interfaces or rules and specifications."* The action of breaking up the system into discrete chunks is a bedrock for the modularity theory. In fact, it is the first step of a process involving decisions that influence the whole system's life cycle. As the previous definitions, this one includes concepts like the interfacing matter, the standardization, and the interdependence.

Gershenson et al. (2003) identify *"three fundamental elements to modularity:*

- *the independence of a module's components from external components,*
- *the similarity of components in a module with respect to their life-cycle processes,*
- *the absence of similarities to external components."*

This extension of the previous definitions points the attention towards the module itself and how it relates to the surrounding components. It also gives a new outlook on how the researchers are introducing a new dimension of the concept: the life cycle orientation.

There it is a variety of intensity in modularity concept: higher degree of modularity means that inside the decomposed object, more modular components or subassemblies can be identified (Ulrich and Tung 1991, Ulrich and Eppinger 1995, Gershenson et al. 1999). This propriety gives the opportunity to the designers to increase gradually the level of modularity, creating more modular parts.

Another aspect that pops up from the literature is the trend of the researchers to identify a number of different types of modularity that could sub-categorize the concept in some more specific and identifiable categories. As the previous definitions, the first step has been the application of this sub-categorization to physical products.

Regarding the different possible product interfaces that could be designed in a product modularization context, Ulrich & Tung (1991) defined three diverse categories of modularity:

- Component-swapping modularity: "*occurs when two or more alternative basic components can be paired with the same modular components creating different product variants belong to the same product family*."

  This definition alludes to the mixing and matching opportunity that modularization enables, permitting to generate variety through component assembly.

  Salvador et al. (2002) makes empirical generalizations about component-swapping modularity: "*When product variety level is low and production volume is high, it is the appropriate type of modularity. […] Firms that choose component swapping modularity limit the negative implications of product variety on operational performance by relying on component family suppliers located near their final assembly facilities and which tend to be smaller or directly controlled by the final assembler.*"

  The previous statement highlights the strong bond that modularization creates between firms and suppliers, particularly emphasizing on the geographical issue connected to the product assembly.
- Component-sharing modularity: "*is the complementary case to component-swapping modularity. With various modular components sharing the same basic component create different product variants belonging to different product families.*"

  Still alluding to the product family, this definition underlines the possibility of using modularized components across
- Bus modularity: "*is used when a module with two or more interfaces can be matched with any number of the components selected from a set of basic components. The module interfaces accept any combination of the basic components. Bus modularity allows variation in the number and location of the basic components in a product while component-swapping and component-sharing modularity allows only variation in the types of basic components.*"

A typical example of bus modularity is the personal computer interface, which allows any type of component that has a standard interface to interact with the core component (i.e. the personal computer)

These three definitions put forth one aspect of the modularization: the interfacing issue. But this property is not enough to define entirely this concept: other essential characteristics have to be determined to define entirely the configuration necessary.

According to Brusoni & Prencipe (2001), *"modularity is a matter of degree. Correspondingly, the degree of modularity depends on the level of analysis. Products can be decomposed at different levels: subsystems (e.g. control system), sub-subsystems (e.g. fuel metering unit), components (e.g. valve) and subcomponents (e.g. spring). Accordingly, modularity can be a characteristic of each or only some of these levels."* This definition reinforces the concept first introduced by Ulrich and Tung (1991): modularity is not a whole system, it can be applied by degrees. This reinforces the theory which says that modularization is characterized by the architecture breakdown of a system into organized subsystems.

Regarding the product families, Jiao et al. (2007) highlight three types of modularity, which are describing the concept from three different points of view on how the modules interact one with one another:

- functional modularity: "*the interaction is exhibited by the relevance of the functional requirements across different customer groups.* ",
- technical modularity: "*is determined according to technological feasibility of design solutions*",
- physical modularity: "*physical interactions derived from manufacturability become the major concern of physical modularity*".

The aim of this work is to set a general definition of the concept of modularization that could be applied to any type of context, without excluding any scope. In the following Tab. 3, the definitions are reported and the main contributions are summed up in synthetic keywords:

	AUTHORS	DEFINITION	CONTRIBUTIONS
MODULARIZATION	Baldwin & Clark (1997)	A set of architecture, interfaces, and standards [...] Modularity is a strategy for organizing complex products and processes efficiently	- univocal characteristics (architecture, interfaces, standards) - decision-making process
	Gu & Sosale (1999)	Modularization allows modules to be produced, assembled and tested in convenient locations with equipment, tools and expertise	- geographical issue
	Ernst & Kamrad (2000)	It implies a product design approach whereby the product is assembled from a set of standardized constituent units. Different assembly combinations from a given set of standardized units give rise to different end-product models and variations. […] It provides opportunities for exploiting economies of scope and scale from a product design perspective. […] Modularization essentially characterizes supplier responsibilities in terms of the outsourcing function.	- standardized units assembly - product variations
	Martin & Ishii (2002)	Fully modularized: the geometry, energy, material, or signal (GEMS) of the component can be changed to meet expected customer requirements without requiring other components to change. This implies that the CI–S (component index-supplying: indicates the strength (or impact) of the specifications that a component supplies to other components.) of the component is zero. Partially modularized: changes in the GEMS of the component may require changes in other components. The higher the CI–S, the more changes expected, and thus the component is considered less modular.	- degree of modularization
	Mikkola & Skjott-Larsen (2004)	An approach for organizing complex products and processes efficiently by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. From a system's perspective, modularization can be perceived as a continuum outlining the degree to which a system's components can be decomposed and recombined. In other words, modularization 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	- complex systems - from physical products only to processes
	Jose & Tollenaere (2005)	It is an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions. It allows the designer to play with combinations of groups of components to develop and customize a larger quantity of products.	- design and process operations involvement - customization - variety
	EMWG (2005)	The process of converting the design and construction of a monolithic plant or stickbuilt scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies	- engineering and contracting - transporting issue
	Kotabe et al. (2007)	A strategic option that goes beyond the physical and functional dimensions of the module that includes an organizational and managerial system linking module integrators and module suppliers to reduce the cost of managing tacit knowledge in the assembly process	- physical and functional characteristics - supply chain involvement - knowledge management process
	Rottke et al. (2012)	The basic idea is to break a complex system down into an assortment of easily manageable components with well-defined interconnections	- interconnections definition

	AUTHORS	DEFINITION	CONTRIBUTIONS
MODULARITY	Starr (1965)	. . . design, develop, and produce . . . parts which can be combined in the maximum number of ways	- life cycle perspective - variety
	Walz (1980)	constructed of standardized units of dimensions for flexibility and Variety in use	- standardized units assembly - variety in use
	Ulrich & Tung (1991)	(1) Similarity between the physical and functional architecture of the design and (2) Minimization of incidental interactions between physical components	- physical and functional characteristics - accidental interactions minimization
	Chan et al. (1994)	relationship between achieving functional independence and reducing the interactions between modules	- functional independence - interactions reduction
	Sanchez & Mahoney (1996)	special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications	- independence or "loose coupling" - standardized interfaces
	Baldwin & Clark (1997)	building of complex product or process from smaller subsystems that can be designed independently yet function together as a whole	- building from subsystems - independent design
	Huang & Kusiak (1998)	the use of common units to create product variants. It aims at the identification of independent, standardized, or interchangeable units to satisfy a variety of functions	- variety - units independence - units standardization - units interchangeability
	Schilling (2000)	Modularity is a general systems concept: it 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. […]At its most abstract level, it refers simply to the degree to which a system's components can be separated and recombined. Since all systems are characterized by some degree of coupling (whether loose or tight) between their components and very few systems have components that are completely inseparable and nonrecombinable, almost all systems are, to some degree, modular	- life cycle perspective - recombination - "loose coupling" - variety - degree of modularity
	Brusoni & Prencipe (2001)	the concept of modularity itself, as put forward in the current literature, is ex definitione static [...] modularity is a matter of degree. Correspondingly, the degree of modularity depends on the level of analysis. Products can be decomposed at different levels: subsystems (e.g. control system), sub-subsystems (e.g. fuel metering unit), components (e.g. valve) and subcomponents (e.g. spring). Accordingly, modularity can be a characteristic of each or only some of these levels	- static concept - degree of modularity - level of analysis

	Langlois (2002)	is a general set of design principles for managing the complexity of such large-scale interdependent systems. It involves breaking up the system into discrete chunks that communicate with each other through standardized interfaces or rules and specifications	- complexity management - system breakup - standardized interfaces
	Gershenson et al. (2003)	three fundamental elements to modularity: • the independence of a module's components from external components, • the similarity of components in a module with respect to their life-cycle processes, • the absence of similarities to external components	- components' independence - module homogeneity - heterogeneity with outside components
	Jiao et al. (2007)	• functional modularity: "the interaction is exhibited by the relevance of the functional requirements across different customer groups. ", • technical modularity: "is determined according to technological feasibility of design solutions", • physical modularity: "physical interactions derived from manufacturability become the major concern of physical modularity"	- different point of view - interaction typing

Tab. 3 List of modularization definitions

Some characteristics are essential to define if the system can be considered as a result of a modularization and some other characteristics are necessary to highlight the major consequences of modularization on the system and on its surroundings.

The three properties that really outstand from the definitions are:

- **The architecture.**

  Most of the time, the researchers allude to physical products (e.g. Ulrich, 1995). In Ulrich's point of view, product architecture is about allocating functions to the physical components by arranging the functional elements, mapping their correspondence with physical components and specifying interactions between physical components.

  Other authors also develop this concept around other areas: Sako (2002) applies the characteristic to organizations, showing the analogies between product and organization architecture. She evaluates the different impacts of organization modularity on three different phases of the product's life cycle. Sanchez (2000) describes the process architecture decomposition analogously to product's architecture decomposition: he points out that both are characterized by the functional "components" and the interactions (analogy with the product interfaces). Voss and Hsuan (2009) introduce the service architecture, still comparing it to product architecture. They set it within the industry context, detailing the different sub-levels by going through the supply chain, then the service bundles and finally the specific service packages/components. This aspect of modularization is very detailed in the current literature, and the most relevant characteristic of it, which is found in most of the fields investigated is the functionality of the system, a concept that is strictly connected to the two following characteristics.

- **The standards.**

  Three levels of standardization are highlighted mainly in the literature:

  - *Commonality*, which is highly correlated with the concept of product family, pulled out by many researchers (Salvador et al., 2002; Gershenson et al., 2003; Mikkola, 2003; Gu et al., 2004; Dobrescu and Reich, 2003; Thyssen et al., 2006). Salvador et al. (2002) allude to the easier supplier chain management, connected to the component sourcing theme.
  - *Compatibility*, which is identified mostly in literature by the platform design: Robertson and Ulrich (1998) refer to platforms in a context of highly competitive product markets, putting emphasis on how important it is to develop multiple products simultaneously at the lowest cost. Another relevant example of it is given by Martin and Ishii (2002), who allude to platform design as the better way to have a fast product development, and develop architectures that may allow to *"reduce future design costs and efforts"*.
  - *Interchangeability*, which is very well developed in the product context and close related to the product flexibility topic. Duray et al. (2000) develop this concept inside the mass customization context, referring to this property as a means *"to achieve the low cost and consistent quality associated with repetitive manufacturing"*. Salvador et al. (2002) relate it with the combinatorial problem, which is strictly connected to the interface definition.

  All the three levels can lead to modularization, with different implications that should be further investigated.

- **The interfaces.**

  They represent a major issue in system modularity, because after deciding the general architecture through the system's breakdown, in fact, the definition of how subsystems interact is the final accomplishment concerning the modular system structure. The major topic cited in literature is the tightness/looseness of coupling, first introduced in the modularization literature by Sanchez (1995). Generally, it portrays the dependence between two systems and highlights a degree of interdependence between them. In the context of the modularization, it is an indicator which allows to establish whether a given interface can belong to the modularized system or not. Sanchez and Mahoney (1996) state that: *"to understand more fully the potential for intentionally decomposing complex product and organizational phenomena into loosely coupled subsystems suggests an approach to gaining new insights into the structure and dynamics of changing product markets and evolving organizational forms."* This decomposition is a basis for systems modularization, in addition to enable design flexibility. In Schilling's (2000) opinion, modularization is enabled *"[...] by uncoupling integrated functions within the components (making the product modular to a finer level)."* This strengthens the theory upon the fact that modularization is a matter of degree.

Another element that characterizes the modularization is the evaluation of the consequences which may occur during the entire system's life cycle. This theme is treated in literature on a macro-level for general aspects (summarized in Tab. 4):

Tab. 4 General life cycle related aspects

The supply chain management plays a leading role across most of the system's life cycle. Hsuan (1999), Doran (2003, 2005), Mikkola and Skjott-Larsen (2004), Howard and Squire (2007), Kotabe et al. (2007) and Hoetker et al. (2007) established that the right setup of the relationship between suppliers and buyers is essential to the success of a modularized system, even if the researchers' opinions on how to deal with it are not going in the same direction (some argue that an arm-length relationship with supplier/buyer has to be established whereas some others think that information sharing and asset specificity may obstruct any kind of close relationship)

Another macro-aspect is the creation of modular consortia and joint ventures, which may enhance the firm's performances regarding the development phase: these global organizational decisions influence the whole firm structure, creating opportunities to innovate, share and test. Marx et al. (1997) give a complete example of an application of these methods in an industrial context (automotive industry in Brazil). In their case, modularization lead to the most integrated outsourcing experience. Pires (1998) underlines various managerial implications that rise from modular consortia: managerial challenges for partners, material flow management, cross organizational teamwork, quality assurance, business opportunities for partners. This shows how the modularization decision touches every aspect of a system, creating implications that have to be considered to make the right choice about modularizing or not. Outsourcing might result as an issue in the following phases of the system's life cycle.

Jungbluth et al. (2000) and Matos and Hall (2007) develop a method for life cycle assessment. This tool is first developed for environmental concerns, is now used to help managers through a wide number of environmental, social, and economical parameters that may interact one with another and influence the system in its different life cycle phases.

Another aspect that impacts globally on a modularized product is the existence of platform based systems or families: Gu et al. (2004) states that life cycle design, once the system reached a certain level of information knowledge, is the most relevant way to design a system, in order to prevent any major hitch in downstream phases: *"the availability of detail information and the diminishing importance of functions make other life cycle objectives the driving factor for modularization."* The existence of a platform or a family accelerates the acquisition of information, allowing to evaluate system's life cycle as early as possible.

Researchers also investigated some more detailed characteristics that have been classified in this work under five main phases:

- **Concept**: Mikkola (2003) is stating that the conceptual stage must already include the complete architecture planning (also the platform must be defined in the cases where the system contains subsystem obtained from a common platform). She also shows how the information flow always starts from the conceptual phase, driving every decision in a particular direction. Moreover, she specifies that suppliers may be involved in the concept *"since the supplier assumes some level of design responsibility and therefore need to be involved in project discussion early in the development process"*. Asan et al. (2004) reduce the modularization process to a core decision among the conceptual design; this statement reduces the complete modularization process to a very punctual decision, which drives the whole concept towards a dead end. Nevertheless, one idea deserves to be underlined: the modularization process they describe is an integrated methodology, which influences every stage of a system's life cycle.

- **Design**: Most of the time, researchers have been investigating this phase to explain the modularization phenomenon. The most recurring modularization characteristics that the literature describes are:
    - Adaptive design: Gu and Sosale (1999) underline how, in cases where the physical configuration is already known, *"the decomposition is the identification of physical components or sub-systems within the product"*. The conceptual base of this statement can be reused in different contexts, e.g. in organizations, where a specified design is already known (by choosing workers that have the same capabilities as the ones who were part of the original design). Gu et al. (2004) state that it is mandatory to have functional independence, because it *"would not only facilitate the adaptation of the existing designs for the new requirements, but make the modification of the existing products easier."* This characteristic, which is defined in contemporary with the architecture, is essential to create modularized systems.
    - Take into account the upcoming phases: Design for manufacturability was investigated by Gershenson and Prasad (1997), who defined a specific manufacturing modularity among the system's life cycle. This represents a part of what modularization has effects on. Design for assembly analysis has been brought to the modularization concept by Gershenson and Prasad (1998), allowing to reduce the assembly costs by increasing preassembly and using common interfaces. Design for testability is introduced by Kusiak and Huang (1997) as a criterion to decide how the system should be broke apart to allow the subsystems to be tested correctly and therefore, have advantages (e.g. quality, less expensive workforce, lower testing costs …). Koren et al. (1999) picture design for reconfigurability as a major achievement in designing manufacturing systems. In this case, flexibility is praised over all the possible qualities of the modularized system.
    - Modules feasibility: This topic arises from the geometric issue in product design: Umeda et al. (2008) tackle the problem by introducing a *"module density"* index, *"which is defined as the ratio of volumes of components to 'approximate modular structure', which is represented as a simply connected*

space of convex hulls that contains all components of a module". This method leads to the best modules evaluation possible. The feasibility issue leads to the modules selection issue: Fujita (2002) shows how the combinatorial problem and the optimization are a central issue in modules selection, then gives two examples where he gets closer to the optimal solution.

- Subsystems into modules: Newcomb et al. (1996) use an algorithm to partition architectures into modules, allowing then to group components that have the highest architectural affinity. Oppositely, Salhieh and Kamrani (1999) sustain that the methods that should be used consists in grouping components into modules, associating components together through a similarity index. These two examples lead to the possibility of using the module as a design parameter: McAdams et al. (1999) refer to exact module incorporation by using exact and sizable modules so that the system is constituted by assembly modules that perform the required function. Ethiraj and Levinthal (2004) describe recombination as the action of using existing modules to enhance performances. Modularization may therefore lead to modules recombination.

All the major decisions regarding modularization are taken in these two first stages and are hardly changeable. Even if the system does not even exist, the decision-makers already have to know what they could expect from it and how it would interact among its context (environment, market, firm …)

- **Development/Construction**: This stage of the system's life cycle is very different, depending on which kind of system is considered: if the system is a physical product (which is the only part that has been investigated by researchers), then this stage matches with the manufacturing and assembly phases (Fredriksson, 2002, 2006; Koren et al., 1999, Heilala and Voho, 2000); if the system is an organization, this stage matches with a hiring/teams building/training phases; if the system is a factory/plant, this stage matches with the procurement/construction phases and so on. An important aspect of this stage is the testing of modules, which is described in literature by Kusiak and Huang (1997) about digital circuits, who describe the possibility of using test modules to perform modular tests. This concept could be enlarged to other kinds of systems.

In these three stages, every decision that has been taken is then applied to the system. Those decisions that have been applied to the system will then have multiple effects on every phase of the system's life cycle and not only on the downstream stages.

- ****Utilization**: Four main aspects of modularization are identifiable at this stage:
  - Reconfigurability, which is very well-known in the manufacturing world as a fundamental feature to obtain flexibility. Mehrabi at al. (2000) state that it may be the key to future manufacturing, arguing that it could lead to a firm that is able to handle change easily by adapting to the latest evolutions of industry or customer needs. Jiao et al. (2007) link this concept to product families and platforms; by reviewing the literature, they mention reconfiguration as a way to create variety, and the fact that modularization may lead to quality loss and costs increase. Gu and Sosale (1999) identify reconfiguration as one of the life cycle objectives of modular design, to allow the accommodation of different needs with little modifications. Hoetker (2006) makes a statement about the definition of modular organizations, telling that modular products lead to more reconfigurable organizations. Karim (2006) establish that reconfigurability is a basic property of modularization, which allows a constant change among the business units. Other authors (Molina et al., 2005; Yigit et al., 2002; Koren et al., 1999; Lee, 1997; Heilala and Voho, 2001) generally discuss the creation of the opportunity of changeability and some of them link it to the quality loss due to modularization. Yim et al. (2007) introduce the theme of self-reconfiguring robots, which may be interesting for further investigations and enlargement of the concept to other scopes.
  - Processes decentralization: in Schilling's (2000) paper, the decentralization is allowed within modular product design contexts, where oppositely to integrated systems, production does not need to be between units in close contact. This is a consequence of the functional interdependence of the production units, which as stated before does not exist in modularized systems. Mehrabi et al. (2000) identify as one of the *"overall trends in various sectors of manufacturing"* the fact that *"the restructuring of organizations emphasizes moving from highly centralized to decentralized team-work (i.e.,*

essentially creating modules and dividing the tasks among them to enhance flexibility, integration, and faster execution of new tasks)". This shows how significant this point is for the modularization's future development inside organizations. Kotabe et al. (2007) see it as a way for module providers to be creative while the production of modules is decentralized. *"Providers are free to experiment with module design, as long as they stay within the design parameter of the standard interface."*

- The degree of modularity was first mentioned by Gershenson and Prasad (1997) who states that *"a higher degree of modularity is more likely to incur a lower total life-cycle cost especially when the entire product family is examined"*. This refers to *"complete modularity"*, which *"may be unrealistic except in the most trivial cases"*. Asan et al. (2004) define it as one of many ways to expand the *"borders of the modular design process"*. They mean that the spectrum that is reached by the modularization process has to be extended to all the subsystems, even those that are part of "non-modularizable" systems. Su and Chuang (2011) apply this concept to the modularization in services, using Mikkola and Gassmann's (2003) assumption: *"the unique components composition in product architecture should vary inversely with the degree of modularity"*. Then other researchers run over the argument, in different contexts (i.e. product architectures in Gershenson et al. (1999), Mikkola (2003) and Fine et al. (2005), relationships between key components in Parente and Gu (2005))
- The identification of "processing" units, in most of the cases cited in literature, is aiming at the system's flexibility: of working units in Tu et al. (2004), by outsourcing in Takeishi and Fujimoto (2001), of organization architecture in Sako (2004), of manufacturing cell subsystems in Rogers and Bottaci (1997).

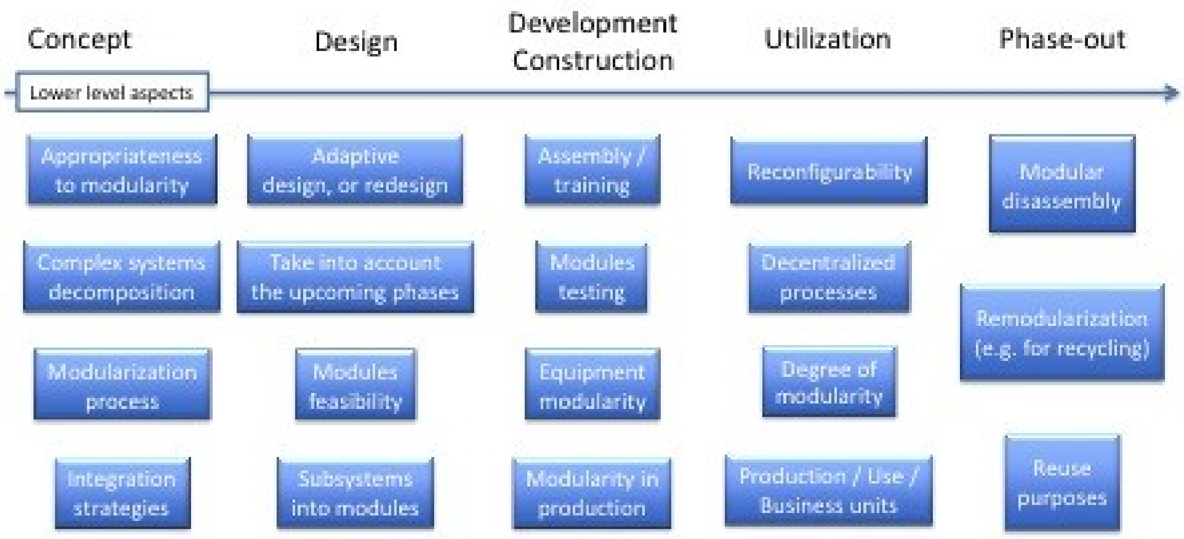
- **Phase-out**: three main elements are cited in the literature:
  - Modular disassembly, which is a concept that researchers mainly attribute to physical products. Newcomb et al. (1996) cite it in the recycling context; they argue that physical products should be designed this way to facilitate materials separation. Duflou et al. (2008) explain that disassembly creates many different possibilities: for physical products, a second hand components' market can be created, since most of the components that are scraped still have residual value. This phase can even be designed to be faster

and less expensive, but it requires that the modularization, which had been applied to the system considered, already includes those design decisions, permitting then to disassembly the system in the most efficient way available. This topic is connected to the functional and physical interaction between components: those connections highlighted by Smith and Yen (2010) and may be the reason for the merging of some modules; Gu and Slevinsky (2003) also mention the disassembly as one of the phases to consider when a mechanical product is modularized. Another aspect of modularization that is brought up by Umeda et al. (2008) is the possibility of recycling of sending to maintenance a complete module, without separating it into components, which could be an expensive operation to perform every time it is necessary.

- Remodularization is brought up first by Lundqvist et al. (1996), who apply the concept to a product line, and give insights of how this project attributes are impacted by managerial decisions. They define it as *"The redefinition of the modular architecture or architectural innovation of the product in question. It mainly includes the reconfiguration of product subsystems and not necessarily changes in functionality or the technical performance of components"*. Langlois (2002) highlights the inevitability of a definitive modularization, then shows how remodularization is, most of the time, a consequence of innovation (the same way Lundqvist et al. (1996) did). As a result of it, some externalities may be generated.
- Reuse purposes: this modularization aspect is very well covered by literature, which consists of 21 papers. Duflou et al. (2008) underlines the necessity of reusing the expensive modules, which are already ready to be integrated in a new system because of the standard interface created by the modularization. Their case study highlights, by context, the profitability of reuse. Gu and Sosale (1999) noticed that the module reusability is determined by the capacity of designers to bundle subsystems with same life duration. In physical products, this property is strongly connected to the detachability of modules from the assembled system. From this point of view, a question arises: "does modularization need to create a system of detachable subsystems or are the modules necessarily removable?" For Garud and Kumaraswamy (1995), reusability arises from the need to give to components a longer life. They see the modularization as a mean to minimize

"performance slippage arising from incompatibility between the newly designed and reused components". Newcomb et al. (1996) draw attention to the importance of how the modules are arranged, when it comes to disassembly, in order to reuse some of the parts. Hady and Wozny (2010) develop a tool (Reuse-Atlas) for engineering reuse using predesigned modules. This tool makes the reuse a systematic method to apply at the end of a system life cycle, creating a knowledge base in the system's area of interest that will be useful to design innovating systems, starting from existing knowledge. Worren et al. (2002) specify that *"the reuse of standard modules should reduce the time of switching between options (compared to integrated designs), as well as the cost of switching"*. Kimura et al. (2001) mention the reuse as a system to create a closed loop life cycle. This vision necessitates to consider which materials are interfacing, what is the components' life duration, and so on. For Umeda et al. (2009), like many other researchers (e.g. Sand et al. (2002)), reuse is part of the lifecycle path designed by the modularization scenario.

The previous phases that have just been described are summarized with their main aspects in Tab. 5:



Tab. 5 Specific life cycle related aspects

This vision of modularization, all along the system's life cycle, shows why some aspects of it make the concept indefinable without these kinds of perspectives. Through the stages of the system's life cycle, one has insights of what to expect from the decisions that will be taken. The global life cycle view connects the concept of modularization with other areas (e.g. the supply chain management, the platform strategies …)

2. The modularization: the concept's boundaries

The review of the concept's boundaries drove towards six major subjects that have been pinned as the most recurring in the literature. Those subjects were obtained by the classification of the keywords inside the framework that has been used to code the papers' information. Then, it has been specified, for every category, of the boundary was referred to external or internal aspects of modularization. The six categories are the following:

- CONTEXT, which is represented locally by *the firm*, which is enclosed in *the market*, which is part of *the global context* or *environment*. Therefore, the boundary is referred to both external and internal aspects of modularization in the decision maker's point of view. This category is covered in literature in every sub-context by a list of arguments, this first list is about *the global context* or *environment*, and represents the boundaries referred to aspects that are external to modularization:
    - Technological change. Many papers from the "early age" of modularization are stating that technological change should encourage the adoption of modularized systems. Sanchez (1995) once argued that while "*radical technological changes leading to new product architectures occur relatively infrequently", modularization can provide flexibility "from reduced difficulty of making a technological shift"*. Later, Sanchez (1999) stated that in the marketing process, modularization can accommodate differential rates of technological change. Schilling and Steensma (2001), in their reasoning about modular organizational forms, identify technological change as the one reason for flexibility when the system is highly modular. They state that this could lead to a decrease of the use of modular organizational forms. In fact, modularization acts as a constraints creator and therefore, shouldn't be used in a fast technology changing sector. More recent work (Kotabe et al., 2007) is sentencing that when modularization happens, the modules identified as the most changing technologically should be outsourced to prevent any negative effect on the system's structure.
    - Changing environments are an issue that is treated by literature as a reason to modularize: the more an environment is static and the less it will need modularization. Schilling (2000) states that this phenomenon causes *"demands or inputs to become more or less heterogenerous"*, and so the system will be more or less subject to modularization. Schilling and Steensma (2001)

notice that *"by breaking their hierarchies down into components that can be fluidly recombined in a variety of production configurations, firms can more quickly adapt to diverse customer needs and changing environments"*. That shows how the system's breakdown makes sense only in cases of changing environments. Finally, Langlois (2002) observes that in the context of modules building, the environmental change makes modularization useful.

- Standards/Design rules. Their existence at a global level allows modular product architecture to exist (Galvin and Morkel, 2001) (e.g. the bicycle industry). Sturgeon (2002) puts standards as a precondition for performance benefits of modularization.
- Intellectual property. Pil and Cohen (2006) show that until the firm possesses it, this firm's competitiveness on the market of a particular modular product may be greater than if the market was sharing the same technology. This is mitigated by the fact that patents need to be divulgated, with release of sensitive information. Oppositely, Fine et al. (2005) state that modularization may occur in a completely non protected environment. The consequences of this assertion is that innovation is pushed but competition may be fierce. Jacobs et al. (2007) underline this issue, explaining that this situation may compromise the relation between supplier and buyer. Finally, Chakraborty et al. (2009) highlight that when modularization is used, the firm is putting in jeopardy its own intellectual property.
- Inputs heterogeneity. Schilling (2000) states that heterogeneous inputs foster the use of modularization that would allow to exploit them to create plenty of different configurations through recombination. She proposes that *"Heterogeneous inputs (diversity in technological options and differentiation in firm capabilities) and heterogeneous demands (customer heterogeneity) will each reinforce the effect of the other"*. This way, one can notice that without this parameter, the implementation of modularization would be a waste of efforts. This aspect is deepened in Schilling and Steensma (2001) upon the modular organizational forms. With *"the availability of standards, the rate of technological change, and the degree of competitive intensity"*, this parameter is helping to determine if modularization is worth it.
- Social systems: They may cause hierarchies to overlap (Schilling, 2000), then finding one-to-one relationships might result more difficult and the

modularization may become harder to conceive. The overlapping with technological systems may threaten a possible reorganization of the system's architecture, therefore obstructing the modularization. Langlois (2002) sustains that the social community may help to achieve cross-fertilization of modularity across firms, with a positive effect on knowledge; but this depends on how this process impacts the social learning community of each firm. This is why social systems remain a modularization close-related context but still doesn't fit inside it.

- Resistance to change. In Schilling's (2000) paper, this aspect is strictly connected to the ability of organizations and social systems to tolerate that the management may choose to implement new production, organization, or design techniques to improve the system's performance. This type of change may be contested even if the environment is pushing towards it.
- Different perceptions. Miller and Elgard (1998) assert that the perception on modularity is depending on the view and scale: the issue arises from the fact that functionality is interpreted differently by the various characters of the system's context/environment. They take as an example, a physical product which may be seen as a product, a module, or a component, depending on who is considering the system.
- Government regulation. As Galvin and Morkel (2001) stated that government plays a major role in the establishment of regulation in terms of standards such as what happens in the bicycle world with the ITU, which is an international body qualified for the *"regulatory and other overseeing bodies"*.
- Geographical spread. Jiao et al. (2007) observe that modularization may arise from the utilization of modules picked from *"geographically dispersed sources"*, that is to say that suppliers may be found on a wider horizon. This may generate a more complicated supply chain and cause longer lead times, due to the transportation issue. Regarding non-material goods, the geographical spread doesn't represent any problem.
- Environmental loads. The life cycle perspective may help to resolve the environmental issue, which is strictly connected with the impact of logistics. Umeda et al. (2008) identify the environmental loads as an interesting aspect to investigate, in order to understand how the different stages of a system life cycle are influencing the impact on the surrounding environment.

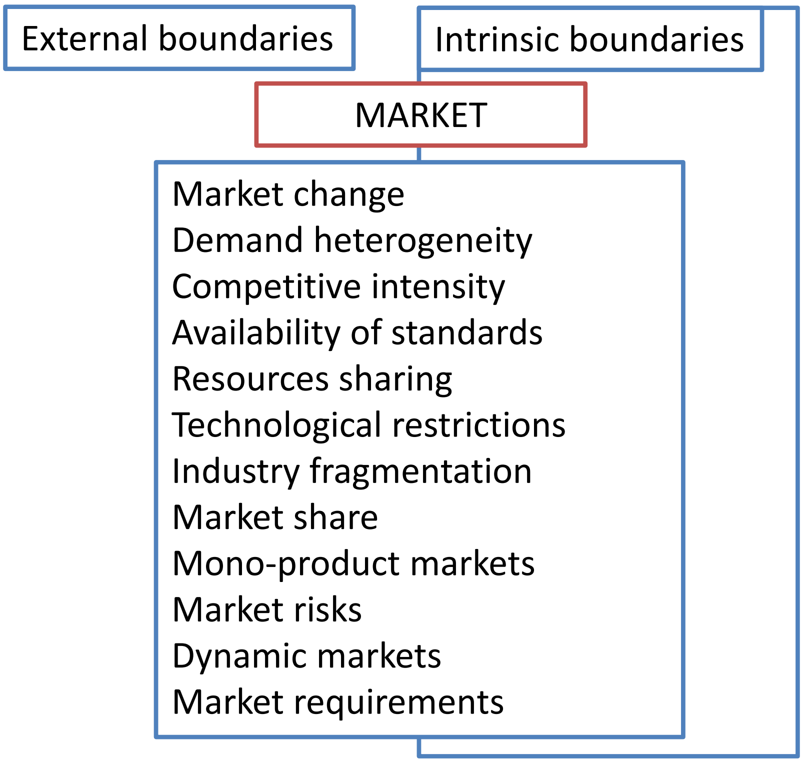
External boundaries	
GLOBAL CONTEXT	
Technological change	Resistance to change
Changing environments	Different perceptions
Standards/Design rules	Government regulation
Intellectual property	Geographical spread
Inputs heterogeneity	Environmental loads
Social systems	Flexibility

Tab. 6 Global context related boundaries

Some other aspects are more precisely related to the market, namely all the conditions dealing with the competitiveness of the firm within a market context:

- Baldwin and Clark (1997) notice that in order to prepare for dramatic changes (like modularization), *"managers need to be able to choose from an often complex array of technologies, skills, and financial options."* They define dynamic markets as *"unforgiving"*. Schilling (2000) highlights that choosing between a modular product rather than an integrated product may drive towards a market share loss. Worren et al. (2002), through their measurement scale, find that a complex relation is linking *"managerial cognition, market context, and the use of modular architectures"*. Sanchez (1999) identifies market uncertainty a major issue, which can be solved through using flexible systems architectures. Helfat and Eisenhardt (2004) analyze how a firm can enter and exit from a market and the implications on the resources deployment essentially. These dynamic conditions, if exploited properly, could lead to significant product-market opportunities. Kotabe et al. (2007) are arguing that the adaptability to market changes may be allowed by a modularized system, therefore, one could suppose that static markets are not suitable for systems' modularization. Parente and Gu's (2005) results show that there is no evidence that market performance and strategic modularization are related, which is leading their research to new issues, like *"the implications of codesign, physical proximity and face-to-face communication can be systematically examined and compared in cross-national strategic relationships"*.

- Some other aspects like material flow (Pires, 1998; Irani and Huang, 2000), technological restrictions (Ernst and Kamrad, 2000), or demand heterogeneity (Kotabe et al., 2007; Miller and Elgard, 1998) are mentioned in the literature.



Tab. 7 Market related boundaries

Finally, some aspects merely specific to the firm context have been highlighted from the literature:

- The cost issue represents a major hurdle to the decision of modularization. Many researchers identify the cost increase associated to the single stages of the life cycle (e.g. design in Karmarkar and Kubat, 1987; production in Tu et al., 2004; Mikkola and Skjott-Larsen, 2004). Other researchers focus on parts of the system that occasion a cost increase (e.g. inventory in Thyssen et al., 2006; Karmarkar and Kubat, 1987; plant in Goldberg and Zhu). Finally, some of them argue upon the cost structure definition (Fujita, 2002) and cost redundancy (Newcomb et al., 1996; Kusiak, 2002).
- The existence of hierarchies may impede the application of the modularization on the system. (Takeishi and Fujimoto, 2001; Sako, 2002; Rivero et al., 2005; Hoetker, 2006)
- Variety may represent an issue strictly related to the costs of modularization, regarding the optimal configuration of modules: Fujita (2002) shows how the

problem of variety optimization consists in three classes of optimization problems. Dobrescu and Reich (2003) show through a model that the optimized product family is characterized by a low variety of components, which create the high variety of products. Chakravarty and Balakrishnan (2001) built a model to determine the right degree of product variety that should be used.

- The technical uncertainties (Zhang and Sun, 2007) may play an active role in the investment decision between modular and integral. Uncertainty also influence the choice of the level of modularization (Gollier et al., 2005)
- Decentralized structures may be an activating factor for modularization, to realize economies of scope (Helfat and Eisenhardt, 2004) or allowing *"innovative firms to enter the industry through producing a single component"*. (Galvin and Morkel, 2001)
- Lundqvist et al. (1996) show how *"the specification of modules is pre-determined, by functional managers, and is part of an explicit strategy"*. Then one can assume that the constraints introduced by the modularization are blocking completely the opportunities of changing design once the process has been started.
- An important limit of modularization is the incompatibility or irrelevancy of the existing stock once a system is modularized/re-modularized. (Langlois, 2002)
- Lundqvist et al. (1996) are stating that too much autonomy of a part of the system could lead to complications when modularizing/re-modularizing. Similarly, the adaptation of an existing system (Collins et al., 1997) may result as a very complicated procedure, due to the existence of an already formed supply chain, which depends on the firm and the system.
- Still talking about supply chain, the modularization may occasion the firm's boundaries to blurry, creating a state of complete dependence from the suppliers. (Kotabe et al., 2007)
- When decomposing a product family different types of modularity are identifiable (i.e. component-swapping modularity, component-sharing modularity, bus modularity). These forms do not permit to identify a single type of modularization among the product family decomposition context. (Huang and Kusiak, 1998)

- For managers, the product modularity strategy may lead to a competitive set of performance features, which allows *"to maximize the impact of limited resources in the face of severe cost pressures"*. (Jacobs et al., 2007)
- Flexibility. Worren et al. (2002) notice that *"some scholars have treated codification and standardization as equivalent to routinization and process stability, and as antithetical to flexibility and innovation"*. This is caused by the consideration of the standardization used in the context of the mass production, which requires high levels of process stability. However, they argue that strategic flexibility could be obtained when the level of architectural knowledge is high. Lier and Gruenewald (2011) observe that flexibility in modular plants may occasion certain risks, which could jeopardize the opportunity created by the availability of flexibility. Muffatto (1999) observed that *"modularisation could introduce rigidity if the full cost benefit were exploited and flexibility must be maintained on model changes"*. In this paper, the main issue of the modularization concept is brought back: the creation of constraints.

Intrinsic boundaries

FIRM

Costs issue	Subsystems autonomy
Existence of hierarchies	Adapt an existing system
Variety	Blurry firm boundaries
Technical uncertainties	Product families
Decentralized structures	Competitive performance
Tasks specification	Flexibility
Obsolescence	

Tab. 8 Firm related boundaries

As it has been presented, the context may help to define in a clearer way which are the modularization's boundaries. Every further specification, from the global context/environment to the inside of the firm, allows to identify the limits, the difficulties and the prerogatives of this concept.

Hereafter, the degree of detail is increased and the boundaries concerning the system's architecture are identified.

- ARCHITECTURE, which concerns every aspect connected to how the system is shaped up. First, the decomposability of the system has to be determined; many authors mention it as a major issue of modularization (Kusiak and Huang, 1997; Huang and Kusiak, 1998; Gu and Sosale, 1999; Langlois, 2002; Ethiraj and Levinthal, 2004). Functional requirements represent a major theme in modularized architecture definition, which has been covered by many authors (Gershenson et al., 2003; Kusiak and Huang, 1996; Fujita, 2002, Salhieh and Kamrani, 1999; Bi and Zhang, 2001; Lundqvist et al., 1996; Sand et al., 2002). The imitation risks are cited by the researchers as one critical aspect of modularization (Worren et al., 2002, Pil and Cohen, 2006; Seliger and Zettl, 2008; Mikkola, 2003). Product families (Huang and Kusiak, 1998) and platforms (Van Hoek and Weken, 1998; Muffatto, 1999; Marx et al., 1997) developed concurrently with the system's modularization allows to reduce lead time and cost of many products at the same time, This aspect is important when one wants to determine if modularization is worth it.

  Another aspect that has to be highlighted is the information structure (Sanchez and Mahoney, 1996; Sanchez, 2000; Fixson, 2007) that is necessary to hold the system architecture together, and provides the means to define the system's organizational context, that is to say its structure (Karim, 2006; Wu and Park, 2009) and boundaries (Lundqvist et al., 1996). The quality of the architecture decomposition determines how the modularization will impact the system. The research of the optimal configuration (Schilling, 2000; Gershenson et al., 2004; Dobrescu and Reich, 2003) and the elimination of the ill-defined modules (Gershenson et al., 2003) are two goals the researchers are aiming to resolve to obtain the most valuable technique. In this terms, the definition of modules characteristics (Kimura et al., 2001) and relationships (Seol et al., 2007) simplifies the multi-module problems (Emmons and Tedesco, 1971) and the selection of modules (Seifert et al., 2012) is easier. Problems connected to the components' lifespan (Gu et al., 2004) may affect the way a system has to be modularized.

  The resistance to change (Schilling, 2000) may create problems to the modularization process which could be resolved partially by the localization of change (Jose and Tollenaere, 2005). Nevertheless, the whole decision depends on the system architecture strategy (Mikkola, 2003) that determines how much the architecture will be static/dynamic (Newcomb et al., 1996; Kusiak, 2002; Voss and Hsuan, 2009) and how much architectural innovation will be permitted (Jiao et al., 2007).

Among the definition of the system's architecture, an inner boundary is drawn, corresponding to the degree of modularity the generic system can bear (Jiao et al., 2007). This limit interfaces with the problem of systems bundling, brought up by Schilling (2000); it represents a contrasting concept compared with modularization. Tab. 9 contains a summary of the architecture related boundaries:

Intrinsic boundaries

ARCHITECTURE	
Decomposability	Product architecture strategy
Functional requirements	Change-resistant architecture
Easy imitation risks	Over-equipment
Platform architecture	Organizational boundaries
Information structure	Multi-module problems
Optimal configuration	Module selection
Modules characteristics/relationships	Individual parts complex functions
Static/Dynamic architectures	Ill-defined modules
Organizational structure	Functional interaction
Subsystems	Module's components common lifespan
Product families	Bundling
Architectural innovation	Degree of modularity
Components customization	Precise localization of change

Tab. 9 Summary of architecture related boundaries

- LIFE CYCLE, which represents the path any system will go through, from the physical product to the organizational form. Every stage contains elements that allow to describe the boundaries of the concept and some other elements are regarding the whole life cycle. By considering the life cycle from an external perspective (Umeda et al., 2008), one can propose different modularization scenarios (Gershenson et al., 2004). Some costs like support activities costs (Thyssen et al., 2006) and capital costs (Carelli et al., 2010) are not attributable to the single stages of the system life cycle, therefore, they contribute globally to the decision whether to modularize or not. Tab. 10 summarizes the main characteristics related to the entire life cycle:

	External boundaries	Intrinsic boundaries	
Entire life cycle	Product life cycle	Different modularization scenarios	Support activities cost Capital costs

Tab. 10 Summary of the boundaries concerning the system's entire life cycle

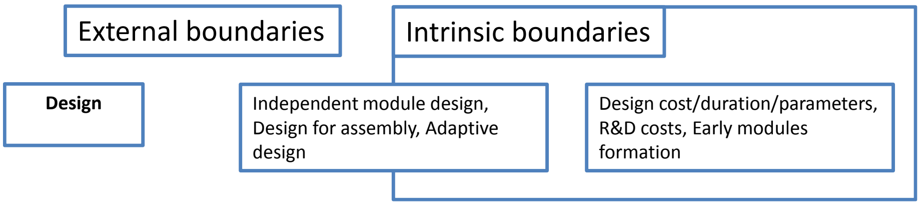
The following sections are detailing the boundaries by stage of the system's life cycle:

- Concept. Every initiative of modularization arises from an opportunity (Mikkola and Skjott-Larsen, 2004) the system gets from the environment, which is then realized in the shape of multiple models (Mikkola, 2003) that modularization allows to be introduced quickly and simultaneously. The modularization can appear easily at this stage if there is a "greenfield" situation (Marx et al., 1997). One negative aspect of modularization that should be foreseen at this stage is the performance degradation (Fixson, 2007) *"due to the use of common components across different products because the common components are most likely non-optimal for any product individually"*. Tab. 11 summarizes the main characteristics related to the concept stage:

	External boundaries	Intrinsic boundaries	
Concept	Opportunity for modularization	Multiple models introduction	"Greenfield" situation Performance degradation

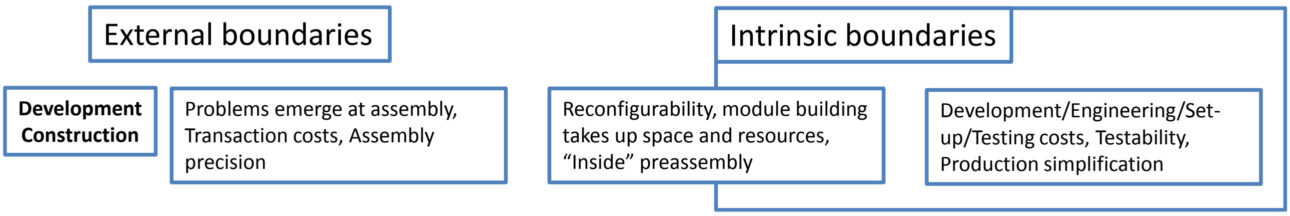
Tab. 11 Summary of the boundaries related to the concept stage

- Design. Two major issues are highlighted in the literature: the adaptive design issue (Gu and Sosale, 1999; Gershenson et al., 2004), which concerns especially the assembly phase, and the independent module design (Huang and Kusiak, 1998), which creates the opportunity of having a very flexible design. The most system's focused aspects of decision upon modularization in design are regarding the costs of design (Garud and Kumaraswamy, 1995; Sako, 2002; Karmarkar and Kubat, 1987) and R&D (Thyssen et al., 2006), the duration of the design phase (Gershenson et al., 2004) and which parameters one decides to use (Kusiak and Huang, 1996; Matos and Hall, 2007; Salvador, 2007). The early formation of modules (Kusiak, 2002) may also create an advantage in favor of modularization. Tab. 12 summarizes the main characteristics related to the design stage:



Tab. 12 Summary of the boundaries related to the design stage

- Development/Construction. The main problem at this stage comes from the assembly precision (Jose and Tollenaere, 2005; Baldwin and Clark, 1997; Langlois, 2002), which may compromise the functionality of the global system. From the economical point of view, this phase is characterized by the transaction costs (Hoetker, 2006) that arise from the supply chain. Those costs may impact on the choice of modularizing, because modularization permits to reduce them. Focusing on the system, one can notice that the elements that essentially allow to take a decision upon modularization are the control of the preassemblies (Fredriksson, 2002), the possibility of reconfigurability (Hoetker, 2006; Yim et al., 2007) and the space and resources pledged by theactivity of modules building (Lier and Gruenewald, 2011), in case of bulky physical systems. More in detail, the costs that a firm has to sustain are regarding: development (Chakravarty and Balakrishnan, 2001; Thyssen et al., 2006; Seliger and Zettl, 2008), engineering (Sako, 2002), set-up (Ulrich, 1995; Sako, 2002; Gershenson et al., 2004), and testing (Garud and Kumaraswamy, 1995). Production simplification (Lundqvist et al., 1996) and testability (Kusiak and Huang, 2007) represent also aspects the managers have to consider when evaluating the choice of modularization. Tab. 13 sums up the main characteristics related to the development/construction stage:



Tab. 13 Summary of the boundaries related to the development/construction stage

- Utilization. The main problem that can be noticed from the outside concerns the obsolescence (Langlois, 2002; Sako, 2002) of the technology used inside the system: this crucial point may force managers to reduce the system's cycle lifespan, when the modularization becomes obsolete. This problem may affect a large number of systems at one time (e.g. case of the product families). Then, more specifically, the redesign (Van Hoek and Weken, 1998; Gershenson and Prasad, 1997; Sand et al., 2002), or the search costs to find economies of substitution (Garud and Kumaraswamy, 1995) may affect the system and create problems that may compromise the competitiveness of the system. Also the costs of maintaining a system modular (Hoetker, 2006) may impact on the choice of modularization in a life cycle perspective. At the system level, one can observe the following issues: the lack of flexibility of the different solutions a manager could adopt (Lier an Gruenewald, 2011; Muffatto, 1999), the upgradeability issue (Umeda et al., 2009), the operations and maintenance costs (Carelli et al., 2010), the will to utilize lean manufacturing (Schilling, 2000). Tab. 14 summarizes the main characteristics related to the utilization stage:

	External boundaries	Intrinsic boundaries	
Utilization	Obsolescence	Redesign, Costs of maintaining modular, Search costs for economies of substitution	Lack of flexibility, O&M costs, Upgradeability, Lean manufacturing

Tab. 14 Summary of the boundaries related to the utilization stage

- Phase-out. Three major aspects have to be taken into account: the recyclability (Gershenson et al., 2004; Seliger and Zettl, 2008; Smith and Yen, 2010) of the system, or parts of it; the reuse (Gershenson et al., 2003) of chunks or modules while the carcass goes to waste, or rethinking of post-life intents (Newcomb et al., 1996); and last but not least, the ease of disassembly (Smith and Yen, 2010), which may be considered also for maintenance: this part may be essential for systems that have an important impact on the ecosystem. Tab. 15 summarizes the main characteristics related to the phase-out stage:

	External boundaries	Intrinsic boundaries	
Phase-out		Recyclability, post-life intent, ease of disassembly	Components' reuse

Tab. 15 Summary of the boundaries related to the phase-out stage

- SUPPLY CHAIN. From the decision maker point of view, the supply chain may be seen as upstream suppliers and downstream buyers. In this section, both have been considered separately, to identify attributes that affect more one or the other:
  - Suppliers: Many of the aspects that determine their ability to take advantage of modularization is connected to their relationship with the customers (Tu et al., 2004), which has to be close and continuous; then this relationship requires a good mutual knowledge (Jiao et al., 2007; Tu et al., 2004; Pekkarinen and Ulkuniemi, 2008). Customer has also to show some kind of autonomy (Hoetker et al., 2007). Risks are represented by the cost of returned merchandise (Mukhopadhyay and Setoputro, 2005) and the bottlenecks (Sanchez and Collins, 2001), that modularization allows to highlight. Finally, the modularization needs to provide value inputs (Mikkola and Skjott-Larsen, 2004; Doran, 2005; Seliger and Zettl, 2008), in order to be worth it.

External boundaries		
Suppliers	Customer knowledge	Close and continuous customer contact
	Customer's autonomy	Highlight capability bottlenecks
	Cost of returned merchandise	Value inputs

Tab. 16 Suppliers related boundaries

  - Buyers: In case they do not represent the final user, buyers need to know their customer needs (this theme is very well covered in the literature, here are the three most cited articles one can find in literature upon this theme: Baldwin and Clark, 1997; Garud and Kumaraswamy, 1995; Stone et al., 2000). Once the needs are identified, it is important to focus on the make or buy decision (Takeishi and Fujimoto, 2001; Sturgeon, 2002), which will condition the choice of modularization in a life cycle perspective. Then, suppliers' management represents a big part of what a buyer has to be aware of, when he starts a collaboration within the supply chain of a modularized product: the supplier selection (Mikkola, 2003) / switching (Hoetker, 2006; Howard and Squire, 2007; Hoetker et al., 2007) may represent an issue if the buyer's technical capabilities are low (Hoetker, 2006). Finally, the specifications negotiation (Hoetker, 2006) may highlight some effects of modularization, brought by suppliers/customers that did not appear to the decision maker when he decided to use modularization.

External boundaries		
Buyers	Customer needs Suppliers' switching Supplier selection Specifications negotiation	Reduced technical capabilities when choosing a supplier Make or buy decisions

Tab. 17 Buyers related boundaries

- Both: The supplier/buyer relationship (Hsuan, 1999; Doran, 2005; Parente and Gu, 2005; Muffatto, 1999) and the supply chain coordination (Kotabe et al., 2007; Pires, 1998) represent a crucial point in the rating of the choice of modularization. The integration with upstream suppliers and downstream customers (Van Hoek and Weken, 1998) may permit to the decision maker's firm to take advantage of the utilization of modularization. The outsourcing (Schilling and Steensma, 2001; Ethiraj and Levinthal, 2004; Mikkola, 2003; Doran, 2003; Fredriksson, 2002) may represent a way to solve problems connected to a missing know how of the decision maker and, through modularization, this could allow to benefit from the situation. Other aspects like resource chains, physical proximity (Kotabe et al., 2007), mutual dependence and fidelity (Sturgeon, 2002; Fine et al., 2005) are hinted at in the literature.

External boundaries		
Both	Outsourcing Supplier-buyer relationships Supply chain coordination Resource chains	Integration with upstream suppliers and downstream customers Physical proximity Mutual dependence, Fidelity

Tab. 18 Boundaries related to both suppliers and buyers

- CAPABILITIES, which the researchers recall in their papers, using them as fundamental tools to make the modularization a rich opportunity. Three types of knowledge are cited in the papers: technological (Sanchez and Mahoney, 1996; Brusoni and Prencipe, 2001; Worren et al., 2002; Ernst and Kamrad, 2000; Hoetker, 2006; Marx et al., 1997), architectural (Sanchez and Mahoney, 1996; Langlois, 2002), and organizational (Sanchez, 2000). Globally, a certain amount of knowledge is necessary to implement modularization, but there could also be a knowledge loss due to the utilization of modularization (Hoetker, 2006). Diverse skills (e.g. planning or engineering in Ulrich (1995); multitasking/coordination in Takeishi and Fujimoto (2001) and Jose and

Tollenaere (2005)) are requested, and a certain level of specialization might be necessary (Schilling, 2000; Schilling and Steensma, 2001). If the capabilities management is lacking, some unpleasant situations can occur: there could be excessive capability (Newcomb et al., 1996; Kusiak, 2002) or oppositely, there could be the risk of losing the core business capabilities (Kotabe et al., 2007). Those aspects could go against the quality (Worren et al., 2002; Jiao et al., 2007; Yigit et al., 2002; Meier and Massberg, 2004) of the system, which may depend on the technical complexity (Mikkola, 2003) of itself, (e.g. in order to preserve the know-how) or the amount of new technologies (Lundqvist, 1996) that the decision maker's firm could benefit of. Another important capability is the value shifting (Doran, 2003; Mukhopadhyay and Setoputro, 2005) ability, that is to say the ability to reconfigure the value chain to adapt the system (e.g. to a modular supply chain).

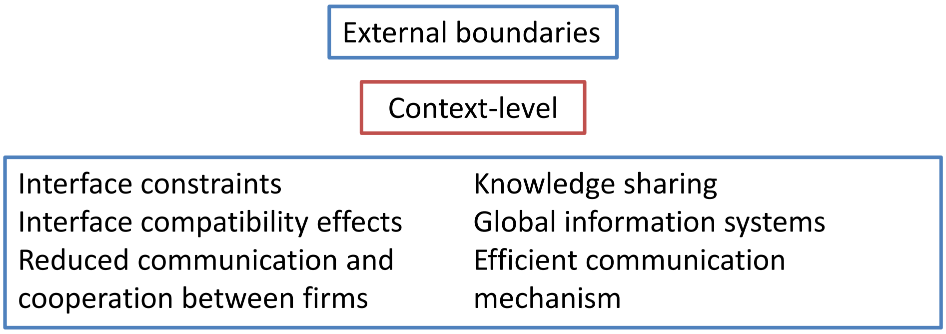
Other capabilities, like autonomy (Hoetker, 2006; Hoetker et al., 2007), scalability (Chakraborty et al., 2009), or other dynamic capabilities (Parente and Gu, 2005) allow an easier implementation of modularization. Despite these aspects, competitors may benefit from the work of firm that use modularization by making use of the reverse engineering (Pil and Cohen, 2006), which may jeopardize the advantages due to modularization.

External boundaries

Knowledge (technical, architectural, organizational)	Risk of losing the core business capabilities
	Reverse engineering
Value shifting	Quality
Level of specialization	Skills (planning, engineering, …)
Excessive capability	Knowledge loss
Autonomy	New technologies
Technical complexity	Multitasking / Coordination
Scalability	Dynamic capabilities

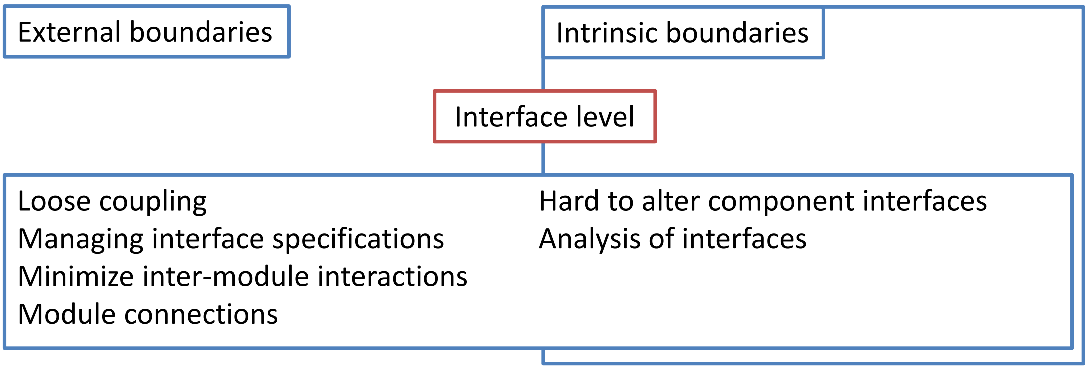
Tab. 19 Capabilities related boundaries

- COMMUNICATION/INTERFACING is the element that describes any type of linking feature that connects subsystems one with one another. These elements may be dictated by the environment/market/context, or could arise from inner decisions that were made to satisfy a certain need. Some interface constraints may be imposed by internationally accepted standards or to have a certain type of compatibility effects (Hsuan, 1999; Mikkola and Skjott-Larsen, 2004); some other communication features may be introduced for a more efficient communication mechanism (Kotabe et al., 2007). For modularization at a global level, there should be a global information system (Sanchez, 1999) that could allow knowledge sharing (Mikkola, 2003), in order to avoid a reduced communication and cooperation between firms (Galvin and Morkel, 2001).



Tab. 20 Interfaces related boundaries, at the context level

Another substantial part regards the interface (any kind of interacting region) definition: generally, the modularization requires module connections (Chakraborty et al., 2009) that are loosely coupled, and permit to manage interface specifications in order to minimize inter-module interactions (Miller and Elgard, 1998). This leads to the analysis of the interfaces (Gu and Sosale, 1999; Gershenson et al., 2004), to determine how subsystems must interact. A particular issue arises from hard to alter component interfaces (Galvin and Morkel, 2001).



Tab. 21 Interfaces related boundaries, at the interface level

Finally, the interaction between the subsystems must be described: the design of interfaces (Newcomb et al., 1996; Muffatto, 1999) leads to a certain type of interface characteristics (Jose and Tollenaere (2005) describe how the complexity of the interfaces may impact on the modularization result), which drives towards a certain level of synergistic specificity (Schilling, 2000; Schilling and Steensma, 2001; Mikkola and Gassmann, 2003; Mikkola, 2006). Modularization requires a certain type of information encapsulation (Baldwin and Clark, 1997; Schilling, 2000; Langlois, 2002; Ethiraj and Levinthal, 2004; Galvin, 1999; Kotabe et al., 2007; Mikkola and Gassmann, 2003) to optimize communication between the parts, which is determined through the interaction analysis (Gu and Sosale, 1999).

Intrinsic boundaries

System level

Information encapsulation Design interfaces Interaction analysis	Complexity of interface characteristics Synergistic specificity

Tab. 22 Interfaces related boundaries, at the system level

The following list summarizes the aspects that have been detailed in this section:

- CONTEXT
- ARCHITECTURE
- LIFE CYCLE
- SUPPLY CHAIN
- CAPABILITIES
- COMMUNICATION/INTERFACING

These categories contain the characteristics the researchers cited in literature that represent a border to the modularization concept.

3. The modularization: connections with the enabling factors and the effects

The connections identified have been separated into two distinct categories, which once completely carried out, give a general picture of how the modularization is connected with any other surrounding concept and performance:

- The enabling factors: that is to say everything that may induce the good conditions to use modularization. This category shows the elements that a decision maker has to take into account when he decides to modularize a system.
- The effects: this category summarizes every aspect that modularization may be responsible of, at a certain point of the system's life cycle. It includes the IMPACTS, which represent the effects endured by the firm which may impact on the system's performance, and the OTHER EFFECTS, not directly related to the system.

This framework helps to identify what kind of information will be contained in the following sub sections.

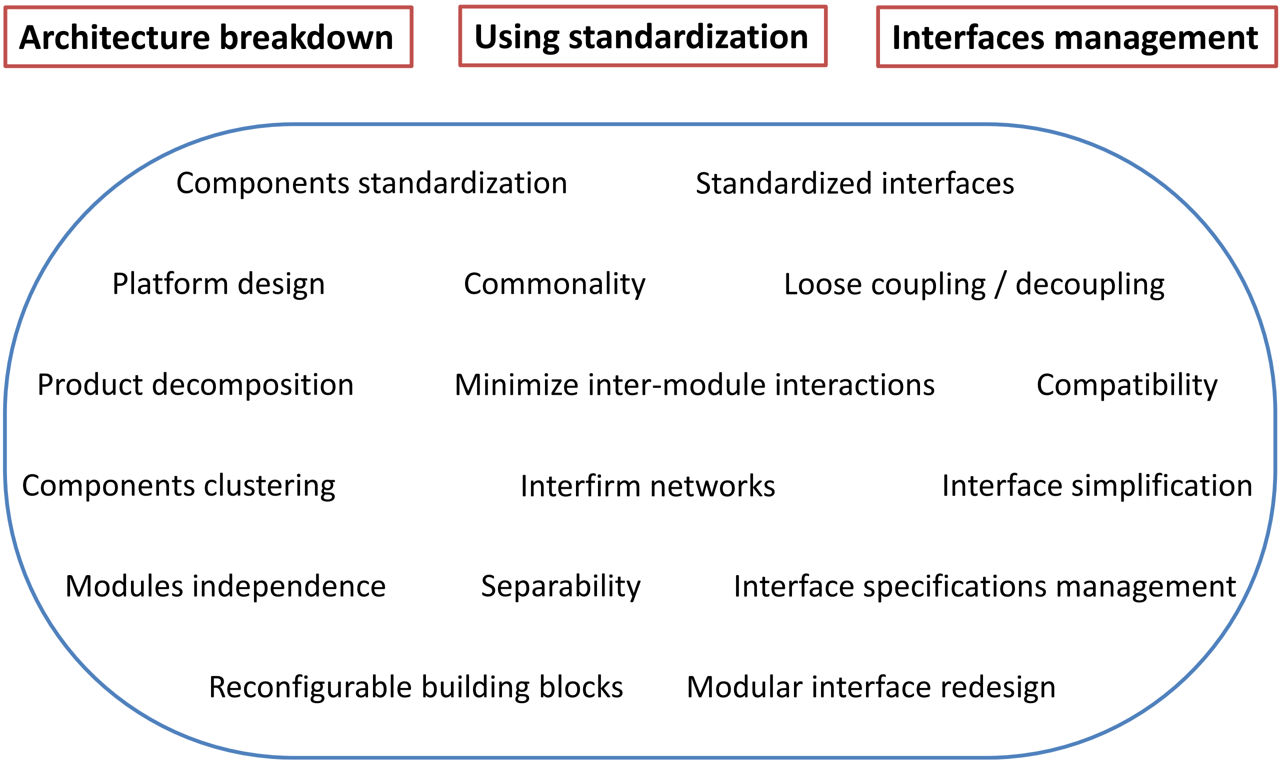
a. Enabling factors

The enabling factors can be grouped under the modularization characteristics they are related to. The categories used to define modularization are also used to define what enables every aspect. First of all, it is essential to describe what is bringing a system close to the conditions that unequivocally define the concept, namely the architecture, the interfaces, and the standards. Those three characteristics, already analyzed in the section where the concept of modularization is defined, need to be configured in a way that allows modularization to be implemented, the following "enablers" are cited in literature as the major activators for the modularization process:

- Product decomposition (Brusoni and Prencipe, 2001; Huang and Kusiak, 1998; Worren et al., 2002; Newcomb et al., 1996) appears as a recurring enabler, which however needs to be accompanied by other fundamental features: regarding the architecture, components have to be clustered (Gershenson et al., 2004; Meehan et al., 2007) in order to obtain modules independence (Newcomb et al., 1996; Gu and Sosale, 1999; Salhieh and Kamrani, 1999; Fujita, 2002; Gershenson et al., 1999, 2003; Asan et al., 2004). This area of study is quite broad, and includes nuances like "loose coupling"/decoupling (Sanchez, 1995, 1999; Sanchez and Mahoney, 1996; Schilling, 2000; Schilling and Steensma, 2001; Galunic and Eisenhardt, 2001;

Galvin and Morkel, 2001; Mikkola and Skjott-Larsen, 2004; Hoetker, 2006; Pil and Cohen, 2006; Salvador, 2007; Jiao et al., 2007) or the concept of separability (Newcomb et al., 1996; Schilling, 2000; Dahmus et al., 2001; Mikkola, 2006; Salvador, 2007). The main result that should foster modularization is to minimize inter-module interactions (Lapp and Golay, 1997; Dobrescu and Reich, 2003; Gershenson et al., 2004).

- Standardized interfaces (because of its wide presence in literature, the papers listed here are the five more recent researches, the other papers can be found in the database. Aurich et al., 2006; Mikkola, 2006, 2007; Salvador, 2007; Jiao et al., 2007) are enabling some properties that push towards modularization. By using simplified interfaces (Newcomb et al., 1996; Van Hoek and Weken, 1998; Muffatto, 1999; Gu and Slevinsky, 2003) and managing interface specifications (Sanchez, 2000; Sanchez and Collins, 2001; Mikkola, 2006, 2007), the decision maker fosters the concept, creating the right conditions for subsystems' compatibility (Langlois and Robertson, 1992; Garud and Kumaraswamy, 1995; Sanchez and Collins, 2001; Nepal et al., 2005) with other architectures. The literature gives a few hints of how modularization could arise from existing systems, through the reconfiguration of the building blocks (Kusiak and Huang, 1996, 1997; Worren et al, 2002; Jiao et al., 2007) and modular interface redesign (Mikkola and Skjott-Larsen, 2004; Mikkola, 2007)
- Finally, the standardization aspect is mainly present in the literature under the concepts of components standardization (He and Kusiak, 1997; Salhieh and Kamrani, 1999; Takeishi and Fujimoto, 2001; Mikkola, 2003, 2006; Tu et al., 2004;) and commonality (Van Hoek and Weken, 1998; Miller et Elgard, 1998; Sanchez, 1999; Kimura et al., 2001; Salvador et al., 2002; Thyssen et al., 2006). This may drive towards a platform design (Sanchez, 1995, 1999; Sanderson and Uzumeri, 1995; Muffatto, 1999; Dahmus et al., 2001; Worren et al., 2002; Jiao et al., 2007) strategy, which is a valuable example of modularization. This standardization may create the opportunity for interfirm networks (Langlois and Robertson, 1992; Ernst and Kamrad, 2000; Schilling and Steensma, 2001; Brusoni and Prencipe, 2001; Dahmus et al., 2001; Fixson, 2007) that foster once again the utilization of modularized systems.



Tab. 23 Main enabling factors of modularization

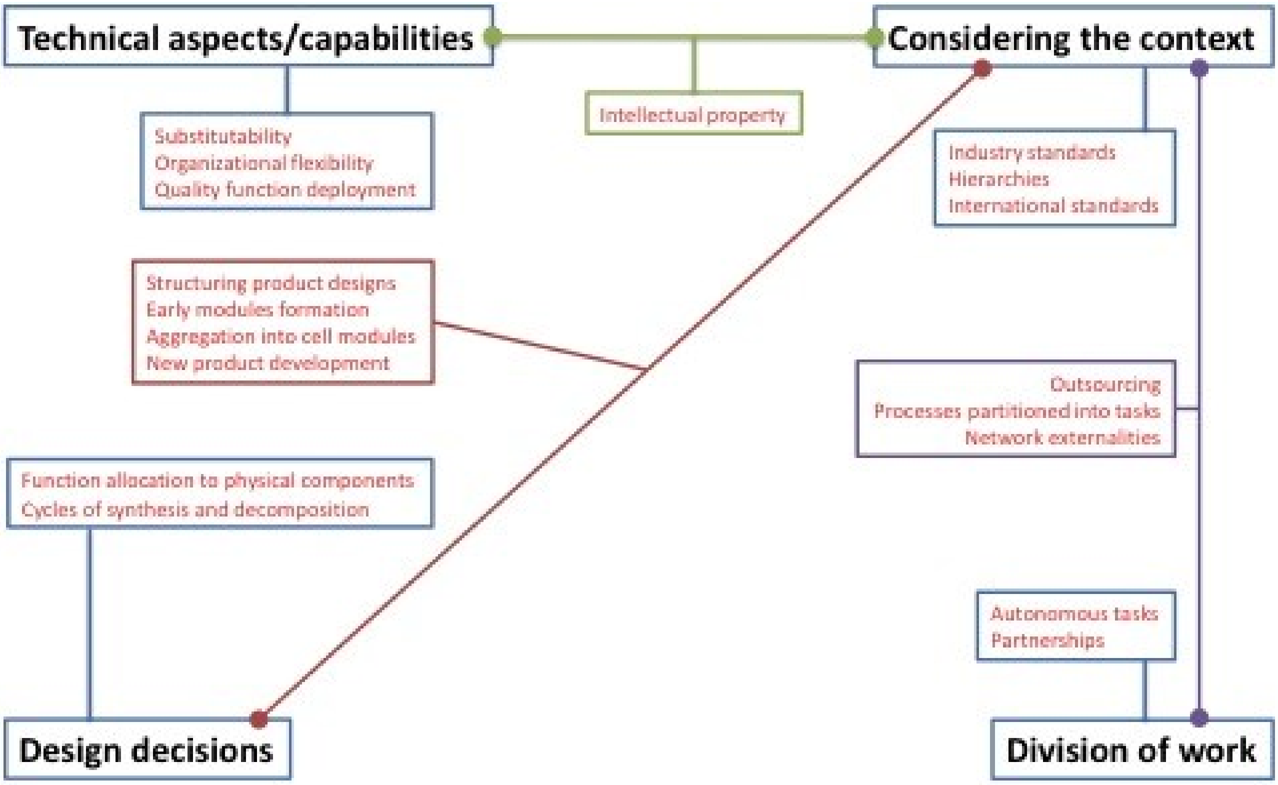
Then, other enablers have been gathered from the papers, linked to four main themes (some enablers are linked to more than one theme, like it is shown in Tab. 24):

- Technical aspects/capabilities: mainly represented by three enablers. The first one is the substitutability (Mikkola, 2003, 2006, 2007; Mikkola and Gassmann, 2003) that allows to any system to have flexibility in maintenance and when new technologies are available. This concept is close related to standardization. Another enabler is the organizational flexibility (Sturgeon and Lee, 2001; Worren et al., 2002), which is a useful feature in inter-organizational relationships. Finally, the quality function deployment (Erixon et al., 1996; Gu and Sosale, 1999) is used as a tool to modularize, helping to *"clarify product design specification"*.
- Considering the context: this point helps the decision maker to consider every condition which may affect the system's efficiency in its context/environment. Industry standards (Sanchez, 1999; Ernst and Kamrad, 2000; Duray et al., 2000; Schilling and Steensma, 2001) and international standards (Sturgeon, 2002; Wallace et al., 2006) are essential to the system in order to develop it coherently with its surrounding. Hierarchies (Sanchez, 1995; Gu and Sosale, 1999) have to be considered, as they represent the closest external constraint to the modularized system. The firm's structure is the first element that has to be in line with the modularization requirements.

- Division of work: this is essential in order to have functional independence between modules. Literature covers two main topics: autonomous tasks (Sanchez, 1995; Sanchez and Mahoney, 1996; Schilling and Steensma, 2001), which decision makers use to confer tasks to the workers, which contribute to create a loosely coupled structure, and partnerships (Collins et al., 1997; Marx et al., 1997; Sturgeon, 2002; Mikkola 2003; Howard and Squire, 2007); those allow to divide the work between diverse firms that sign a contract that binds them together.
- Design decisions: once the system is defined, the first thing to do is to allocate functions to the components (Fixson, 2007). This process permits to make a more founded decision about modularization, that is to say, the decision maker is able to identify the logical and physical link between the components before he takes any decision about modularizing or not. Another helpful enabler the researchers are mentioning is the realization of *"cycles of synthesis and decomposition in modular product architecture creation"* (Sanchez, 2000), which is allowing to group efficiently common elements together.
- Finally, some elements that are belonging to two categories at the same time, are listed hereafter:
  - The *context* and the *design decisions* share the following enablers: structuring product designs (Ulrich, 1995; Sanchez and Mahoney, 1996), early modules formation (Kusiak and Huang, 1996), which arises from a disposition of the system that combines components naturally; aggregation into cell modules (Benjaafar et al., 2002), and new product development (Mikkola, 2006), which may foster the decision maker to use modularization on the newly designed system.
  - The *context* and the *division of work* share: the outsourcing (it represents an important part of the literature linked to the modularization concept, which brings the researchers to discuss about it: Ernst and Kamrad, 2000; Takeishi and Fujimoto, 2001; Worren et al., 2002; Salvador et al., 2002; Mikkola and Skjott-Larsen, 2004; Jose and Tollenaere, 2005; Mikkola, 2006; Jiao et al., 2007; Howard and Squire, 2007), the partitioning of processes into tasks (Sanchez and Mahoney, 1996; Duray et al., 2000), and the network externalities (Sanchez, 1999; Schilling, 2000; Langlois, 2002), which may

generate learning across firms and enable a virtuous process the modularization will benefit of.

- The *technical aspects/capabilities* and the *context* share: the intellectual property (Fine et al., 2005), which gives to the firm who uses modularization a shield to contrast concurrence from imitation (Mikkola, 2003).



Tab. 24 Other enablers of the modularization

b. Effects

The effects are divided into two types: the system's performance, and the other effects, which are characterized by a more general value to the firm. Firstly, the performance is described, and the different aspects are divided into eight major categories:

- The impact on economics is the main subject that is treated in literature. It represents everything the decision maker is going to spend, spare, sell, invest, etc. Modularization is illustrated in the literature as a driving force to realize economies of scale (covered in the past ten years by the following articles: Carelli et al., 2010; Mikkola, 2007, 2006, 2003; Fredriksson, 2006; Thyssen et al., 2006; Jose and Tollenaere, 2005; Mikkola and Skjott-Larsen, 2004; Mikkola and Gassmann, 2003; Gershenson et al., 2003) and substitution (Mikkola, 2007, 2003; Mikkola and Gassmann, 2003; Schilling, 2000; Sanchez, 1995; Garud and Kumaraswamy, 1995), which represent two useful techniques that allow the firm to manage costs efficiently: the economy of scale is pushing towards bigger systems made of many similar modules (a good example is brought by Carelli (2010) who employs more than one SMR instead of a unique large size reactor), while economies of substitution are stimulating the replacement of modules across product families with cheaper modules (Schilling (2001) is showing how some modules may be reused in other product designs). The impact on costs is perceivable all along the life cycle (Gershenson and Prasad, 1997; Gershenson et al., 2003; Mikkola and Gassmann, 2003; Jose and Tollenaere, 2005; Zhang et al., 2009), that is to say it concerns every stage from design; here are some examples:

- design reusability in Jiao et al. (2007),
- transaction (Mikkola (2003) explains how *"trustworthiness within the trading relationship reduces transaction costs and increases the likelihood that transactors will invest in relation-specific assets"*),
- processing (Gershenson et al. (2003) explain how modularity helps containing those costs),
- development (Mikkola and Gassmann (2003) refer to suppliers as a way to reduce the development cost of a subsystem),
- inventory/stock (e.g. the higher commonality is, the lower the inventory cost will be (Van Hoek and Weken, 1998)),
- set-up,
- production (manufacturing (e.g. using Design For Manufacturability technique as suggested by Gershenson and Prasad (1997)) and assembly (e.g. using life cycle modules (Newcomb et al., 1996))),
- tooling,
- transport/logistics (linked to the economies of scale concept),
- distribution (e.g. *"modular product architectures become a means to achieve several forms of strategic flexibility"* said Sanchez (2000)),
- maintenance/service (same example as the assembly stage),
- phase out (e.g. disassembly is cheaper is modules are already arranged by materials, dangerousness, etc.).

The financial impact is also playing a major role in modularization competitiveness: the initial investment (Sanchez, 2000; Lier and Gruenewald, 2011; Seifert et al., 2012) is reduced due to, for example, the possibility of enabling concurrent and distributed development of components.

Under the sales perspective, modularity may generate an increase of revenues. Though, this might be counterbalanced by an increase in design cost (Mukhopadhyay and Setoputro, 2005). This aspect is therefore to consider in conjunction with the cost model (e.g. Karmarkar and Kubat, 1987) employed, resulting then as a tradeoff decision.

Impact on economics

- Savings (e.g. economies of scale/substitution, life cycle costs, transaction costs, initial investment, …)
- Expenses (e.g. inventory, switching costs, logistics, …)
- Sales-related (e.g. competitiveness, Sales, …)
- Tools availability (e.g. cost models, cost characteristics, …)

Tab. 25 Modularization's impact on economics

- Time plays a major role in the competitiveness of a firm and the success of a system. It involves many aspects of the system performance that are aiming to obtain a time reduction (Sanchez, 1995, 1999; Huang and Kusiak, 1998; Duray et al., 2000; Ernst and Kamrad, 2000; Brusoni and Prencipe, 2001; Salvador et al., 2002; Gershenson et al., 2003; Ethiraj and Levinthal, 2004). This may be obtained, for example, by scheduling (Carelli et al., 2010; Zhang et al., 2009; Wallace et al., 2006) the development of the modularized or programming concurrent tasks (Ulrich, 1995; Sanchez, 1995; Sanchez and Mahoney, 1996; Gu and Sosale, 1999; Gershenson et al., 2003). Productivity (Lara et al., 2005; Muffatto, 1999) improvement may be a consequence of the changes brought by modularization. An important time-related risk that can be mitigated with modularization is the obsolescence (Rogers and Bottaci, 1997; Schilling, 2000; Parente and Gu, 2005), which is slowed down, due to the availability of alternatives for subsystems and that innovation push developers providing new technologically advanced modules to keep the product up to date.

  Other effects like job turnaround time (Kotabe et al., 2007; Parente and Gu, 2005) and switching time (Sanchez, 1995; Worren et al., 2002) are cited by researchers. They contribute to improve the modularized system.

Time- related impacts • Duration • Concurrent tasks • Scheduling	• Obsolescence • Job turnaround time • Switching time • …

Tab. 26 Time related impacts on modularization

- The impact on quality represents the value-adding actions or attributes that are obtained from the utilization of modularization. The researchers identify in their papers the improved attributes:
    - testability (Ulrich, 1995; Huang and Kusiak, 1998; Gershenson et al., 2003; Sako, 2002; Miller and Elgard, 1998) allows to check regularly the functionality of the modules assembled,
    - specialization (Koren et al., 1999; Galunic and Eisenhardt, 2001; Brusoni and Prencipe, 2001; Sturgeon and Lee, 2001; Mikkola, 2003; Mikkola and Gassmann, 2003; Jose and Tollenaere, 2005) is enabled by the improved in-depth analysis of every module (if some modules are outsourced, even if it does not come from the decision maker's firm, the specialization exists, because the supplier focuses on the development of the module: the module is his final product),
    - serviceability (Newcomb et al. (1996) remind it as a benefit of modularity),
    - robustness (Yim et al., 2002; Yim et al., 2007) comes from the ability of grouping parts of the systems together in order to have synergy inside the module or because the system is constituted by identical parts that are able to recombine themselves optimally.

The research of the quality fosters innovation diffusion (Galvin, 1999; Fixson, 2007), which comes from the specialization will of the module teams. It also leads to the identification of the critical components (Mikkola and Gassmann, 2003), which pop up when the modules are designed and developed, way earlier than if the system was all in one piece.

The major impacts on quality are therefore: a greater value perceived by the consumers (Gershenson and Prasad, 1997; Takeishi and Fujimoto, 2001), the optimization of the system's design (Fujita, 2002), a greater detail of the product features (Duray et al., 2000), and a better flow of information across the firm (Howard and Squire, 2007).

Impact on quality	
• Testability	• Critical components identification
• Specialization	• Design optimization
• Value for consumers	• Product features
• Serviceability	• Information flow
• Innovation diffusion	• …
• Robustness	

Tab. 27 Modularization's impact on quality

- Variety is obtained through the increased configuration options (Koren et al., 1999; Schilling, 2000) that have been enabled by the possibility of mixing and matching. Modularization creates the opportunity of taking advantage of the economies of scope (Garud and Kumaraswamy, 1995; Duray et al., 2000; Ernst and Kamrad, 2000; Salvador et al., 2002; Helfat and Eisenhardt, 2004; Tu et al., 2004; Mikkola and Skjott-Larsen, 2004), which allows the system's firm to reduce the average cost of producing more than one product contemporarily. The general impact perceived is a global increase of variety (this theme is widely described in literature, the following papers are the latest published: Voss and Hsuan, 2009; Jiao et al., 2007; Meehan et al., 2007; Kotabe et al., 2007; Mikkola, 2007; Salvador, 2007; Fixson, 2007), which some authors define as differentiation (Pekkarinen and Ulkuniemi, 2008) or diversity (Gershenson et al., 2004). The fact is that modularization, while creating variety, allows to decrease the components variety and, in case of physical products, the different materials used (Newcomb et al., 1996); this last statement may be enlarged to every kind of system, by replacing the word "material" with the inner characteristics of the system's components.

Impact on variety	
• Economies of scope	• Different materials
• Component variety	• Differentiation
• Configuration options	• Diversity
• Mixing & matching	• Service variety
• Variety	• …

Tab. 28 Modularization's impact on variety

- The strategic flexibility (Sanchez, 1995; Sanchez and Mahoney, 1996; Huang and Kusiak, 1998; Sanchez, 2000; Galvin and Morkel, 2001; Worren et al., 2002; Gershenson et al., 2003; Tu et al., 2004) and the independence of the modules (Newcomb et al., 1996; Gu and Sosale, 1999; Gershenson et al., 1999;

Salhieh and Kamrani, 1999; Fujita, 2002; Gershenson et al., 2003; Asan et al., 2004; Pil and Cohen, 2006) are drivers of the action of modularization, in order to obtain flexibility of the modularized system. Through that, the researchers identify the principal aspects activated: the adaptive potential (Galunic and Eisenhardt, 2001) of the system has increased and one can design, from scratch, flexible products (Ulrich, 1995; Sanchez, 1995; Sanchez and Mahoney, 1996; Gershenson and Prasad, 1997; Ethiraj and Levinthal, 2004). The characteristics enabled are interchangeability (Langlois and Robertson, 1992; Gershenson and Prasad, 1997; Miller and Elgard, 1998; Van Hoek and Weken, 1998; Sanchez, 1999; Gershenson et al., 2003; Mikkola, 2003; Jiao et al., 2007), reconfigurability (Baldwin and Clark, 1997; Gu and Sosale, 1999; Mehrabi et al., 2000; Jiao et al., 2007; Salvador, 2007), and reusability (Kusiak and Huang, 1997; Gershenson et al., 2004; Gu et al., 2004; Nepal et al., 2005). This may lead in some cases to agile manufacturing (He and Kusiak, 1997; Watanabe and Ane, 2004) and to future flexible responses to system's changes (Sanchez and Mahoney, 1996; Kusiak and Huang, 1996; Galvin and Morkel, 2001).

Impact on flexibility

- Strategic flexibility
- Interchangeability
- Flexible products designs
- Reusability
- Flexibility in changes
- Agile manufacturing
- Independent modules
- Adaptive potential
- Reconfigurability
- …

Tab. 29 Modularization's impact on flexibility

- Modularization has influence on the system's risks: many researchers praise the ability of modularization to reduce the overall risks (Garud and Kumaraswamy, 1995; Huang and Kusiak, 1998; Brusoni and Prencipe, 2001; Kusiak, 2002; Strugeon, 2002; Gershenson et al., 2003; Zhang and Sun, 2007). Others hint at the inventory risks (Salvador et al., 2002; Mikkola and Skjott-Larsen, 2004; Jacobs et al., 2007) and the market risk (Gollier et al., 2005) as potential areas of risk reduction when the modularization is employed on the system. Modularization properties push towards a context where the opportunism is limited and the potential risks depend on the suppliers' choice (Hoetker, 2006), which depends on how many responsibilities (Pires, 1998) have been assigned to him, and the potential radical innovation (Pil and

Cohen, 2006), which would jeopardize the modularization effort. However, one of the effects of modularization on a physical product is the stabilization of the manufacturing process (Baldwin and Clark, 1997).

Risks related impacts	
• Overall risks	• Suppliers responsibility
• Inventory risk	• Technical uncertainties
• Radical innovation	• Uncertainty
• Opportunism	• Suppliers choice
• Manufacturing process stabilization	• …

Tab. 30 Risk related impacts on modularization

- Scalable capacities (Lier and Gruenewald, 2011) and the start of collaborations (Mikkola, 2003; Howard and Squire, 2007) fosters the modularization to pursue the system's maximal efficiency. The efficiency occasioned by modularization is first expressed formally as a greater speed to market of the system (Sanchez, 1999, 2000; Mookken and Haddad, 2006; Kotabe et al., 2007; Lier and Gruenewald, 2011; Seifert et al., 2012). The tasks are performed with an increased autonomy (Mehrabi et al., 2000; Fredriksson, 2002; Howard and Squire, 2007), which permits to perform tasks concurrently (as it has been already specified in the previous section about time related impacts). The system's productivity (Muffatto, 1999; Lara et al., 2005) is affected by the modularization in a positive way, thanks to an easier manufacturing process (Kimura et al., 2001); in this context, modularization fosters the adoption of easy to install components (Garud and Kumaraswamy, 1995; Sanchez and Mahoney, 1996; Ernst and Kamrad, 2000; Gershenson et al., 2003). At the same time, in this same manufacturing context, the dimensions of the WIP inventory can be reduced (Ernst and Kamrad, 2000; Jacobs et al., 2007); however, the finished products' inventory may grow, due to the variety of assemblies generated. Some researchers also sustain that the modularization allows waste reduction to happen (Parente and Gu, 2005; Kotabe et al., 2007). Finally, due to the organized structure of modularization, the decision maker can obtain a greater energy efficiency (Lier and Gruenewald, 2011).

Impact on efficiency • Speed to market • Easy-to-install components • Autonomy • Productivity • Inventory	• Waste • Easier manufacturing • Energy efficiency • Collaborations • Scalable capacities • …

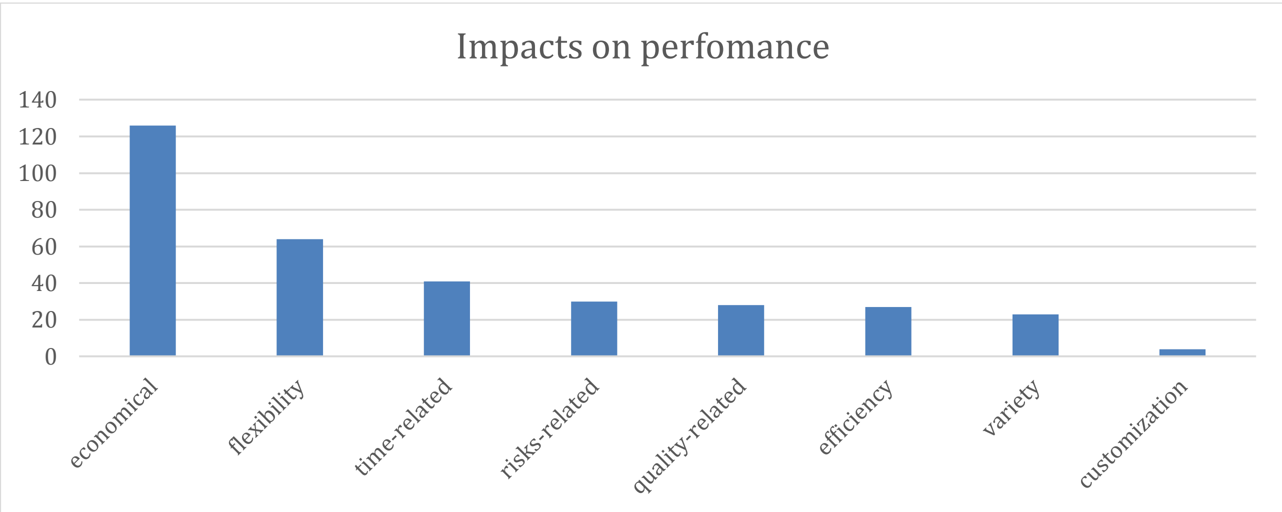
Tab. 31 Modularization's impact on efficiency

- The modularization gives the opportunity for customers to customize the good they are purchasing. Researchers investigate the components' customization (Hsuan, 1999), which generally is necessary to reach mass customization (Gu and Sosale, 1999; McAdams et al., 1999; Gershenson et al., 2003; Tu et al., 2004), which is a more and more widespread phenomenon. Voss and Hsuan (2009) describe a facet of customization in services, which *"can either be combinatorial, in which various service processes and products are combined to create a unique service, or menu driven, in which personnel (or even the customers) select from among existing services/products to meet customers' needs"*.

Customization impact • Component customization	• Service customization • …

Tab. 32 Customization impact on modularization

The following Diag. 5 summarizes the entity of every effect described previously. The economical aspect is the most cited, as on could expect.



Diag. 5 Impacts on performance of the different effects described

Those characteristics describe the main effects that modularization causes on the system's performance. The other effects that influence the firm because of the utilization of modularization are the following:

- Capabilities availability, which have been divided into four distinct categories.

  First, the elements related to the knowledge, which consist in the intellectual reuse (Miller and Elgard, 1998) of knowledge acquired when the modularization was accomplished. This aspect is closely related to the knowledge transfer (Rogers and Bottaci, 1997; Worren et al., 2002; Hoetker, 2006; Karim, 2006; Kotabe et al., 2007), which is necessary to maintain the firm's knowhow across time; this concept is applicable outside the modularization context. In the same way, the joint development ventures (Baldwin and Clark, 1997) that the firm has formed will remain an asset beside modularization. Then examples like lean manufacturing (Takeishi and Fujimoto, 2001), that may create benefits for modularization, are an expertise that stays in the firm's know how.

  Second, elements developed in the human resources context for modularization will persist. For example, the increased specialization (Koren et al., 1999; Galunic and Eisenhardt, 2001; Brusoni and Prencipe, 2001) or the increased complex technology handling (Baldwin and Clark, 1997; Tu et al., 2004) could be used in new contexts. Employees acquire features that contribute to enrich the firm's capabilities:

  - the different approach to coordination (Sanchez, 1995; Sanchez and Mahoney, 1996; Schilling, 2000; Galvin and Morkel, 2001; Ethiraj and Levinthal, 2004; Fredriksson, 2006),
  - the autonomy (Mehrabi et al., 2000; Fredriksson, 2002; Howard and Squire, 2007),
  - the serviceability (Newcomb et al., 1996; Gu and Slevinsky, 2003), the habit to job turnarounds (Parente and Gu, 2005; Kotabe et al., 2007) are changing permanently the firm's framework.

  Third, the inclination to foster flexibility, due to the numerous constraints the modularization brings, permits to be prone to substitutability (Mikkola and Gassmann, 2003; Mikkola, 2003, 2006, 2007), adaptation (Sanchez, 1999; Galunic and Eisenhardt, 2001; Ethiraj and Levinthal, 2004; Gu et al., 2004), versatility (Yim et al., 2002, 2007), therefore to be able to cope with rapidly changing markets (Galvin and Morkel, 2001), to reconfigure supply chain (Hoetker, 2006) after the rise of a particular issue, or even scale the capacity (Lier and Guenewald, 2011) to adapt to customer's needs.

  Fourth, the inclination to sustainability fosters the firm to behave properly in order to respect the environment: as it has been specified in the impacts context, the reduction of waste (Parente and Gu, 2005; Kotabe et al., 2007) and the reusability (Kusiak and Huang, 1997; Gershenson et al., 2004; Gu et al., 2004; Nepal et al., 2005) are a permanent benefit for the firm, which is training the employees and the whole milieu to a certain behavior.

Capabilities availability

Human resources related
- Coordination
- Autonomy
- Increased specialization
- Increasingly complex technology handling
- Serviceability
- Job turnarounds
- …

Knowledge related
- Knowledge transfer
- Intellectual reuse
- Joint development ventures
- Lean manufacturing
- …

Flexibility
- Adaptation
- Versatility
- Coping with changing markets
- Supply chain reconfiguration
- Scalable capacity
- Substitutability
- …

Sustainability related
- Reusability
- Waste reduction
- …

Tab. 33 Capabilities available thanks to modularization

- The literature review provides also an overview of all the tools available for the analysis of modularization. Those tools are then reusable in other different contexts. The following table summarizes them, and indicates which articles are using them:

TOOL	Papers	
atomic theory	Smith and Yen, 2010	
clustering methods	Lapp and Golay, 1997 Gershenson et al., 2004	Tseng et al., 2008
computer-aided plant design	Hady and Wozny, 2010	
cost model	Karmarkar and Kubat, 1987 Gershenson et al., 2004	Wallace et al., 2006 Zhang and Sun, 2007
cost penalty method	Lapp and Golay, 1997	
design structure matrix	Newcomb et al., 1996 Takeishi and Fujimoto, 2001 Gershenson et al., 2004 Sosa et al., 2004 Matos et Hall, 2007	Seol et al., 2007 Meehan et al., 2007 Jiao et al., 2007 Smith and Yen, 2010
failure rate model	Hoetker et al., 2007	
fuzzy logic approach	Nepal et al., 2005	
genetics algorithms	Jose and Tollenaere, 2005 Tseng et al., 2008	Meehan et al., 2007 Jiao et al., 2007
Holonic Product Design method	Gershenson et al., 2004	
integer programming	Brandes et al., 2008	

rewards	Garud and Kumaraswamy, 1995 Galunic and Eisenhardt, 2001 Sanchez, 2000 Helfat and Eisenhardt, 2004
sensitivity analysis	McAdams et al., 1999 Sered and Reich, 2006 Chakravarty and Balakrishnan, 2001 Duflou et al., 2008 Gollier et al., 2005 Voss and Hsuan, 2009 Mukhopadhyay and Setoputro, 2005
service modularity function	Voss and Hsuan, 2009
software tool	Seliger and Zettl, 2008 Rottke et al., 2012
strategic drivers	Sako, 2002
strategic learning	Sanchez and Collins, 2001 Mikkola, 2006
task structure matrix	Lara et al., 2005
weighted goal programming	Fine et al., 2005

Tab. 34 Tools used in the modularization literature

- The firm may benefit of innovation practices introduced during the modularization. Globally, it allows to improve other firm's functions and bring technologically advanced solutions in different divisions (e.g. the IT advances as mentioned by Sanchez (1995) and Schilling (2000)) for a general diffusion of innovation (Galvin, 1999; Fixson, 2007). One type of innovation is fostered by modularization, that is to say incremental innovation (Sanderson and Uzumeri, 1995; Galvin and Morkel, 2001; Worren et al., 2002), while unfortunately architectural innovation (Ulrich, 1995; Galvin, 1999; Galunic and Eisenhardt, 2001) and radical innovation (Pil and Cohen, 2006) are harder to develop. However, changeability practices (Erens and Verhulst, 1997) are pushed to encourage the general flexibility of the firm.

  The components' creation and improvement (Galvin and Morkel, 2001) are enjoyable also for non-modularized products, and this may foster the firm to continuous improvement (upgrades, add-ons and adaptations (Mikkola, 2003; Jose and Tollenaere, 2005)) and technological change (Sanchez, 1995; Schilling, 2000; Schilling and Steensma, 2001). The burst of modularization practices enabled numerous forms of derived product models (Sanchez, 1995, 1999) and module variations (Mikkola, 2003; Gu et al., 2004), thanks to the interchangeability property (Gershenson and Prasad, 1997; Miller and Elgard, 1998; Gershenson et al, 2003) and the possibility to change individually the modules (Gu and Sosale, 1999; Schilling, 2000; Gershenson et al., 2003). And important aspect developed with the modularization practice is the learning aspect:
  - Interfirm learning (Collins et al., 1997; Mikkola, 2003)
  - Learning-by-leveraging and Learning-by-planning (Sanchez, 2000)

Innovation practices

- Architectural innovation
- Incremental innovation
- Radical innovation
- Technological change
- Individual module change
- Interchangeability
- Derived product models
- Module variations
- Upgrades
- Add-ons
- Adaptations
- IT advances
- Innovation diffusion
- Interfirm learning
- Changeability
- Components' improvement
- Learning-by-leveraging
- Learning-by-planning
- …

Tab. 35 Innovation practices related to modularization adoption

- Supply chain practices that are remaining after modularization has been implemented, are mainly regarding the supplier-buyer relationships (Doran, 2003; Mikkola and Skjott-Larsen, 2004; Kotabe et al., 2007; Hoetker et al., 2007). More in detail, the developed aspects concern the customer management (Worren et al. (2002) hint at the customer needs, Garud and Kumaraswamy (1995) highlight the importance of providing customers with continuity, Tu et al. (2004) explain how much a supplier can take advantage of the assembly, for example, into customer sites). Moreover, material handling and quality control management (Takeishi and Fujimoto, 2001) are valorized. In physical products' contexts, firms may take advantage of the assembly simplicity (Newcomb et al., 1996; Muffatto, 1999; Fujita, 2002; Gu and Slevinsky, 2003) introduced by the modularization. From the customer's point of view, suppliers' production lines may be connected to the firm (Pires, 1998; Benjaafar et al., 2002) in order to optimize the logistics of the WIP.

  More generally, the interfirm coordination (Garud and Kumaraswamy, 1995; Brusoni and Prencipe, 2001) is taken into account way more than before, leading the firm to closer collaborations with the most valuable suppliers/customers. The awareness of these potentialities may push towards contract manufacturing (Ernst and Kamrad, 2000; Schilling and Steensma, 2001; Ethiraj and Levinthal, 2004). Also inventory management (Ernst and Kamrad, 2000; Jacobs et al., 2007) changes, by adopting some of the modularization characteristics.

Supply chain practices	
• Supplier-buyer relationships	• Interfirm coordination
• Inventory management	• Customer management
• Assembly simplicity	• Material handling management
• Contract manufacturing	• Quality control management
• Modular assembly into customer sites	• ...
• Connected supplier production lines	

Tab. 36 Supply chain practices related to modularization adoption

- There are a few effects that impact the organizational design and practices: the embedded coordination (Galvin and Morkel, 2001) generated by the introduction of modularization fosters the reduction of management pressure over the design process (Sanchez and Collins, 2001; Hoetker, 2006), which allows to the employees to develop a local and more accurate management (e.g. organizational design reconfiguration in Hoetker (2006)), though keeping a centralized coordination and control (Helfat and Eisenhardt, 2004), held by the managing committee of the firm. Moreover, this delegation of decision-making power is fostering firm specialization (Mikkola, 2003; Mikkola and Gassmann, 2003) through organizational modularization. Those new ways of approaching organizational architecture lead the firm towards organizational innovation (Tu et al., 2004). An interesting issue regarding the introduction of modularization in the firm traditions is represented by the problem of stabilizing processes (Baldwin and Clark, 1997), but through the knowhow acquired on how *"to create families of parts that share common characteristics"*, this may not result as a limit to modularization.

Organizational design and practices	
• Specialized firm	• Embedded coordination
• Less management over the design process	• Innovation
• Centralized coordination and control	• Stabilize processes
• Organizational design reconfiguration	• ...

Tab. 37 Organizational design and practices related to modularization adoption

- Last but not least, modularization provides a set of strategic management practices that may result useful for the firm in certain situations, like in any issue involving complex systems management. Some more general guidelines or strategic drivers (Sako, 2002) induce the managers to fix specific objectives that stimulate the entire firm to *"go modular"*. The most significant feature is the alliance formation ability (Baldwin and

Clark, 1997; Schilling and Steensma, 2000; Langlois, 2002; Ethiraj and Levinthal, 2004) which might result as a motor for strategic learning (Sanchez and Collins, 2001; Mikkola, 2006) and knowledge sharing between the R&D departments of different firms. Modularization has also effect on:

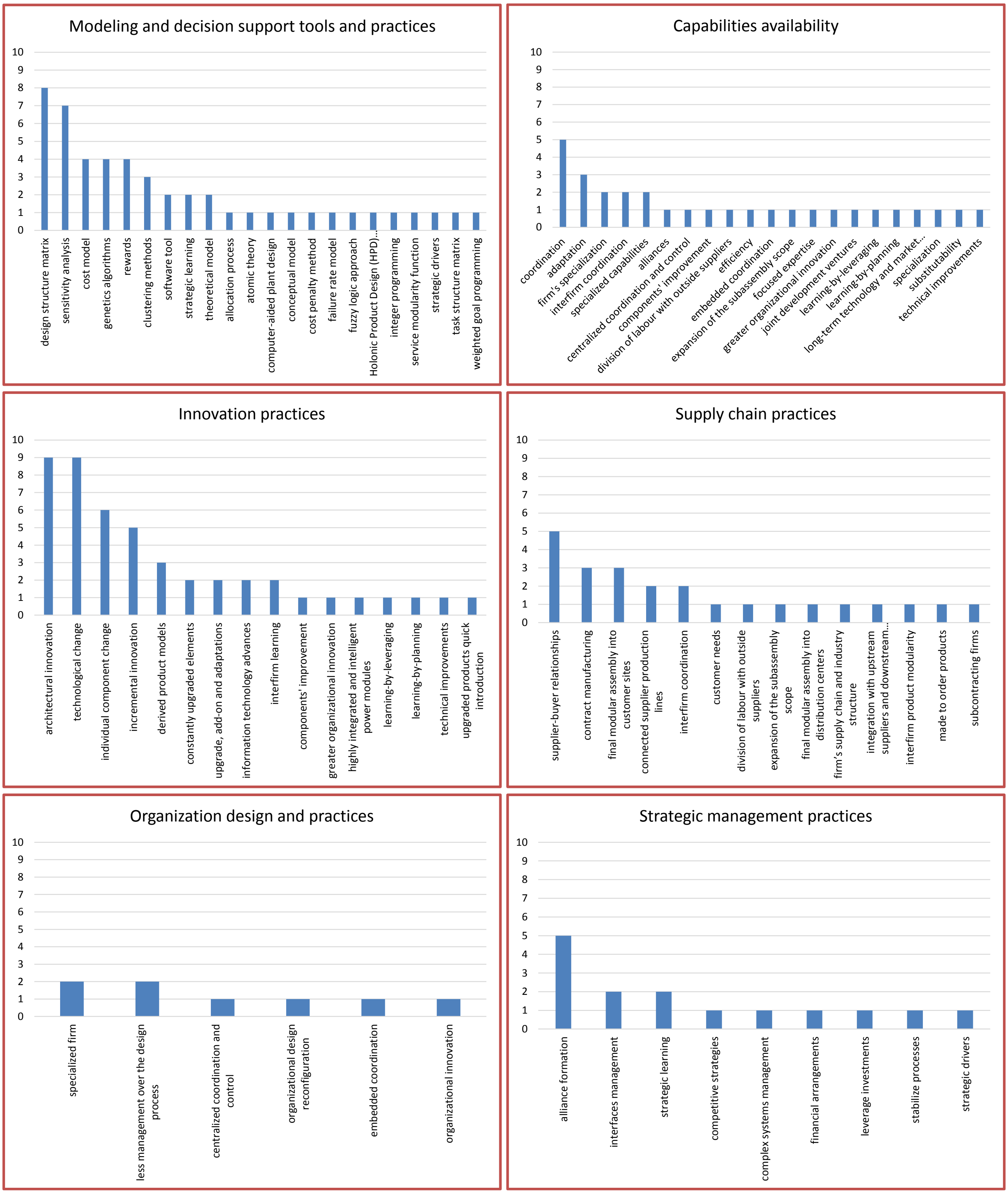
- interfaces management (Sanchez, 2000; Sanchez and Collins, 2001; Mikkola, 2006, 2007), which are then a major design parameter for any firm's system,
- competitive strategies (Sanchez, 1999), among the concept of modular architectures.

Furthermore, the head of management can benefit of financial arrangements (Baldwin and Clark, 1997) and therefore aim for leveraging the investments (Garud and Kumaraswamy, 1995).

Strategic management practices	
• Alliance formation	• Financial arrangements
• Interfaces management	• Leverage Investments
• Strategic learning	• Strategic drivers
• Competitive strategies	• …

Tab. 38 Management practices related to modularization adoption

All the previous effects described are summarized by the following Diag. 6, which displays how many times every characteristic is cited in literature.



Diag. 6 Other effects' relevance in the literature (number of papers per keyword)

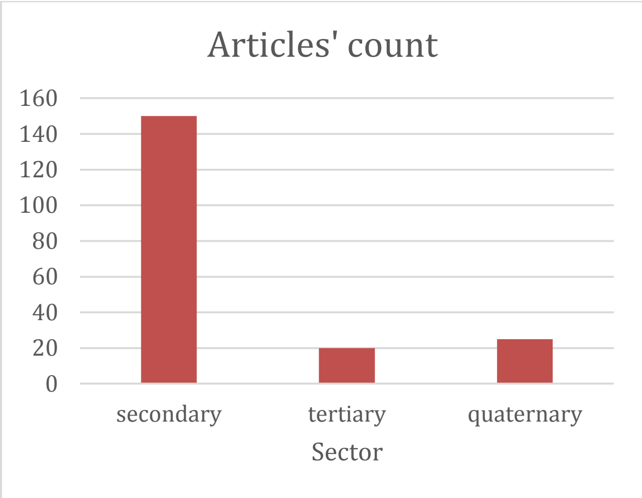
4. Open issues

The review of the literature leads to some considerations upon the existence of unsolved issues among the concept of modularization. This involves certain aspects that have been covered in the review of the literature, and some others that are arising from general considerations one can make. One main issue remaining is summarized in the following question: "where do I cut a system to accomplish the modularization? And how will the selected cut be identified as the best way to decompose the system?" This question is opposed to the very well covered issue regarding the clustering of components into modules (Lapp and Golay, 1997; Gershenson et al., 2004; Meehan et al., 2007; Tseng et al., 2008; Brandes et al., 2008), which has been a common point of view in the modularization literature. Considering the entire system and subsequently, decomposing it into chunks (Stone et al., 2000) is a practice that has not been yet developed by a sufficient number of researchers to be considered as a significant design technique.

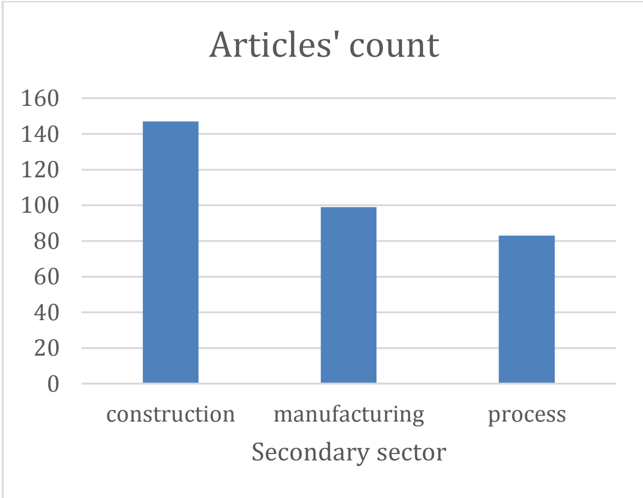
Decomposing a system into modules forces the firm to define a certain number of well identified and standardized interfaces. This decision requires a particular attention, because it represents an important and expensive design choice, which is affecting most of the downstream stages of the system's life cycle. The simpler way to approach this issue is to consider the tradeoff between the number of modules interfacing one with the other and the level of modularization, that is to say the depth of the decomposition of the system into subsystems, as it has been defined by Brusoni and Prencipe (2001). This subject requires further investigation.

Another main issue concerns the life cycle assessment, which is not mentioned in most of the definitions of modularization, even if the researchers practice in-depth investigations of the different stages of the system life cycle. Still, there is no hint to the fact that this concept causes a chain of events, which consequences may jeopardize the quality, functionality or even the convenience of the modularized initiative. This major lack in scientific literature does not facilitate the practitioners to carry with certainty the theory from the journals into the real application contexts.

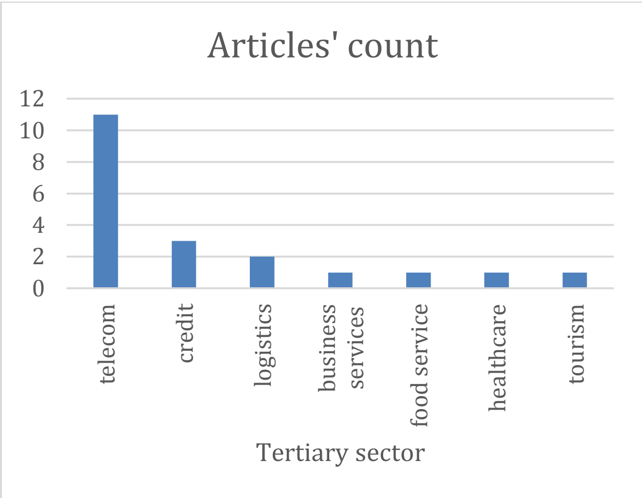
Then, the distribution of the papers among the different sectors of economy has to be underlined: as it is shown in Diag. 7, the sector of economy, which is more represented in the modularization literature, is the secondary sector. Diag. 8 shows that the sub-sectors of the secondary are equally well covered by the papers, whereas the tertiary (Diag. 9) and the quaternary (Diag. 10) are not as developed. As it has been said at the beginning of the introduction, the secondary sector has been the first field covered by researchers (mainly the product design field); this is the reason why this sector is more developed. This shows how many branches of the economy still could be investigated by the scientific community, before modularization could be seen as a universally defined concept.



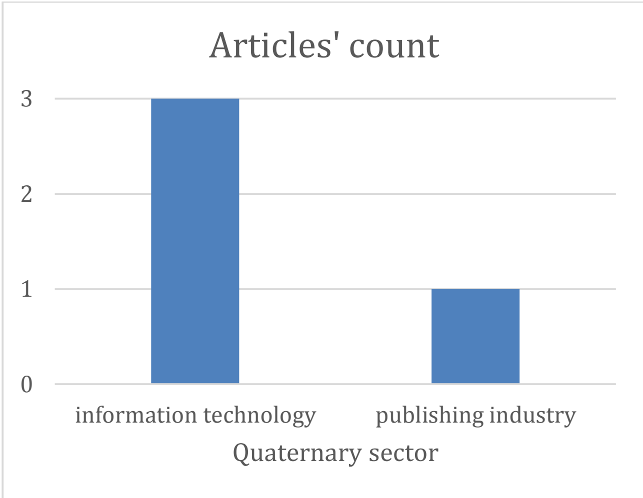
Diag. 7 Number of articles per sector



Diag. 8 Secondary sub-sectors dealt with



Diag. 9 Tertiary sub-sectors dealt with



Diag. 10 Quaternary sub-sectors dealt with

The literature offers to the practitioners a certain number of definitions, which may confuse the reader: most of the definitions given by the researchers are related to specific contexts analyzed in their paper. This is not what most of the practitioners may be looking for, when they decide to investigate what the scientific community has been studying. A first interest may be over the most universal definition, which may help a generic decision maker/manager to understand what he is heading towards.

In Tab. 39, the definitions of modularization found in the literature are critically reviewed, to highlight the aspects that may narrow their field of application. The next section includes an attempt to take the cue from those critical aspects, and define an ontology of the concept of modularization.

	AUTHORS	DEFINITION	Critical aspects
MODULARIZATION	Baldwin & Clark (1997)	A set of architecture, interfaces, and standards [...] Modularity is a strategy for organizing complex products and processes efficiently	- There is no hint to the life cycle aspect.
	Gu & Sosale (1999)	Modularization allows modules to be produced, assembled and tested in convenient locations with equipment, tools and expertise	- It misses the whole structural aspect of a system's modularization
	Ernst & Kamrad (2000)	It implies a product design approach whereby the product is assembled from a set of standardized constituent units. Different assembly combinations from a given set of standardized units give rise to different end-product models and variations. […] It provides opportunities for exploiting economies of scope and scale from a product design perspective. […] Modularization essentially characterizes supplier responsibilities in terms of the outsourcing function.	- It does not mention any interface characteristics - It refers to the product in a bottom-up vision, which excludes the real choice of modularization: "where do I cut?"
	Martin & Ishii (2002)	Fully modularized: the geometry, energy, material, or signal (GEMS) of the component can be changed to meet expected customer requirements without requiring other components to change. This implies that the CI–S (component index-supplying: indicates the strength (or impact) of the specifications that a component supplies to other components.) of the component is zero. Partially modularized: changes in the GEMS of the component may require changes in other components. The higher the CI–S, the more changes expected, and thus the component is considered less modular.	- It is a partial definition of the extent of modularization. It does not refer to neither the system breakdown to nor to standards.
	Mikkola & Skjott-Larsen (2004)	An approach for organizing complex products and processes efficiently by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. From a system's perspective, modularization can be perceived as a continuum outlining the degree to which a system's components can be decomposed and recombined. In other words, modularization 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	- The utilization of the word "complex" narrows the definition's applicability. - It does not refer explicitly to standards to adopt
	Jose & Tollenaere (2005)	It is an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions. It allows the designer to play with combinations of groups of components to develop and customize a larger quantity of products.	- The utilization of the word "complex" narrows the definition's applicability. - It does not refer explicitly to standards to adopt - No hint to interfaces
	EMWG (2005)	The process of converting the design and construction of a monolithic plant or stickbuilt scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies	- Narrowed to the plants applications - Neglects interfacing and standards aspects
	Kotabe et al. (2007)	A strategic option that goes beyond the physical and functional dimensions of the module that includes an organizational and managerial system linking module integrators and module suppliers to reduce the cost of managing tacit knowledge in the assembly process	- It alludes exclusively to supply chain aspects
	Rottke et al. (2012)	The basic idea is to break a complex system down into an assortment of easily manageable components with well-defined interconnections	- The utilization of the word "complex" narrows the definition's applicability. - No hint to standards

Tab. 39 Definitions of modularization and their critical aspects

V. Literature-grounded ontology

An ontology includes 3 main elements, which are represented in Fig. 2:

1. An extended definition of the concept and its attributes,
2. The concept's boundaries,
3. The relationships between the concept itself, the enabling factors (I) and the effects (O).

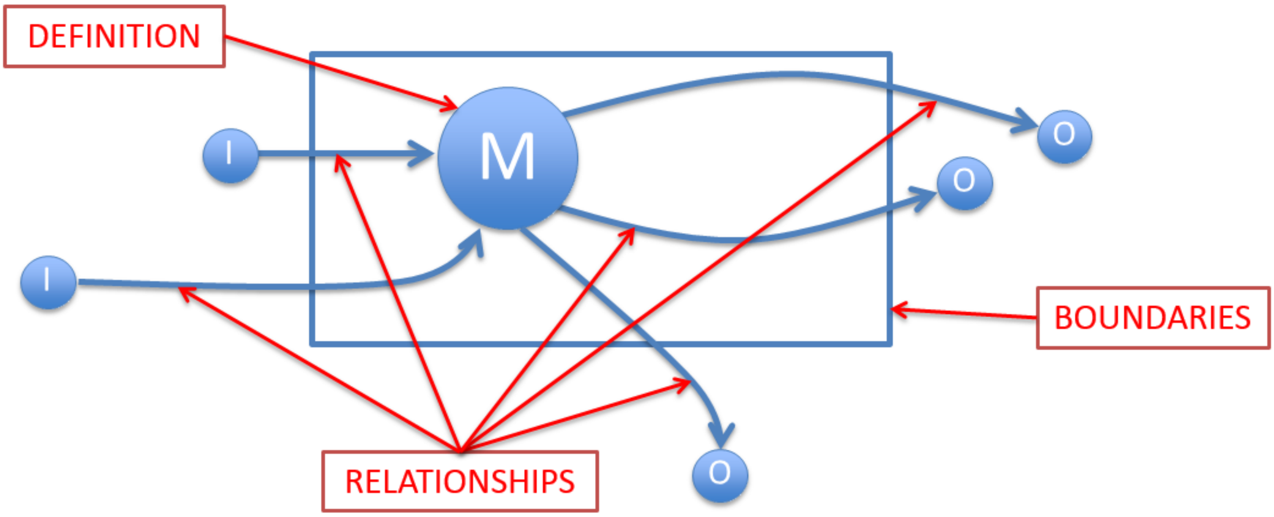


Fig. 2 Representation of the modularization concept

1. Definition

The review of literature has highlighted the most relevant aspects linked to the modularization issue. As it has been shown, there are plenty of different definitions given by the researchers that are valid in some specific scopes or that partially explain the phenomenon.

The intent here has been to gather the valid and most general properties of modularization, in order to define the concept in its most general meaning. The result is expressed by the following definition, which is then represented in Fig. 3 in a schematic map:

"Modularization consists in a configuration of a socio-technical system through its architecture breakdown into standard and functional subsystems, which are interfaced to operate together as a whole and may impact on all the system's life cycle. Both its achievement and justification should arise from a life cycle-oriented decision-making process."

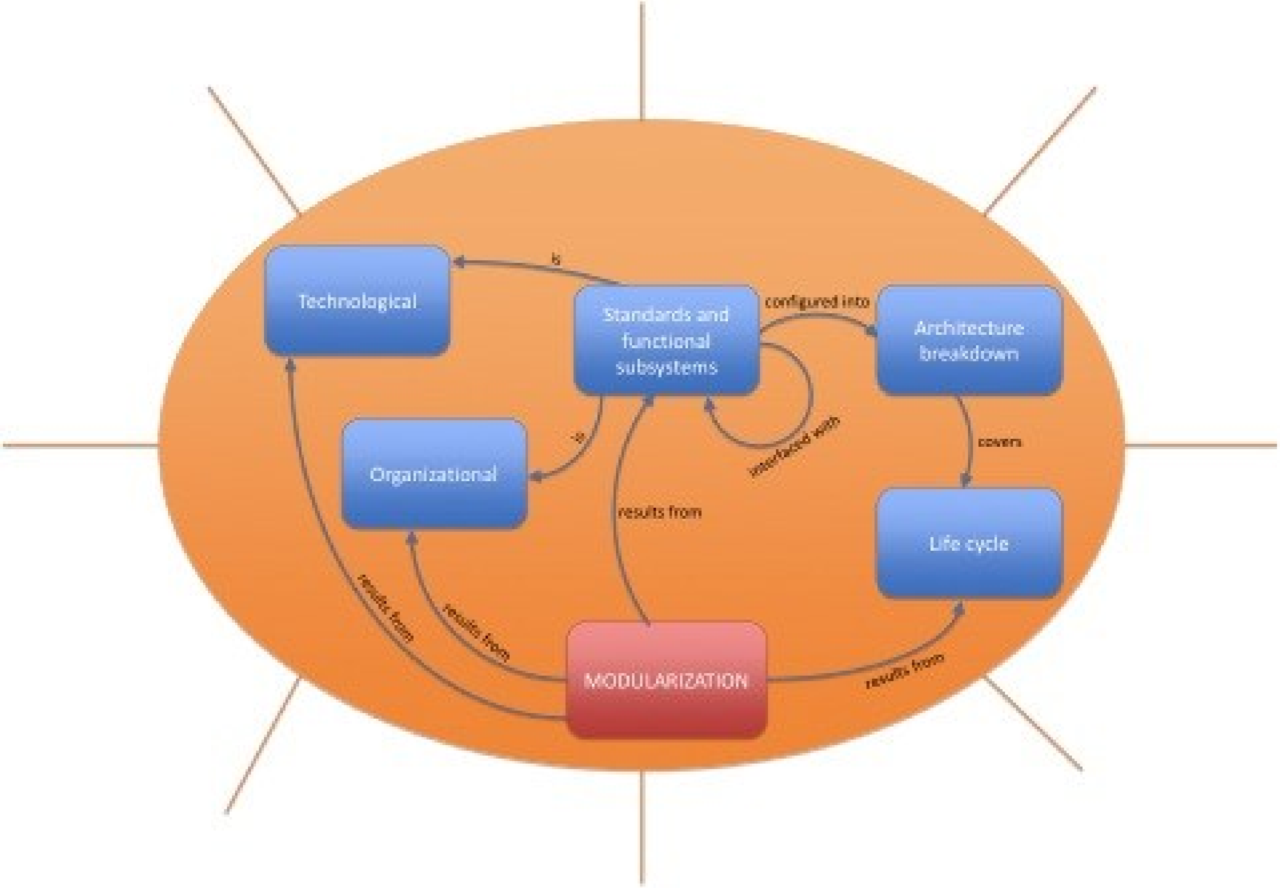
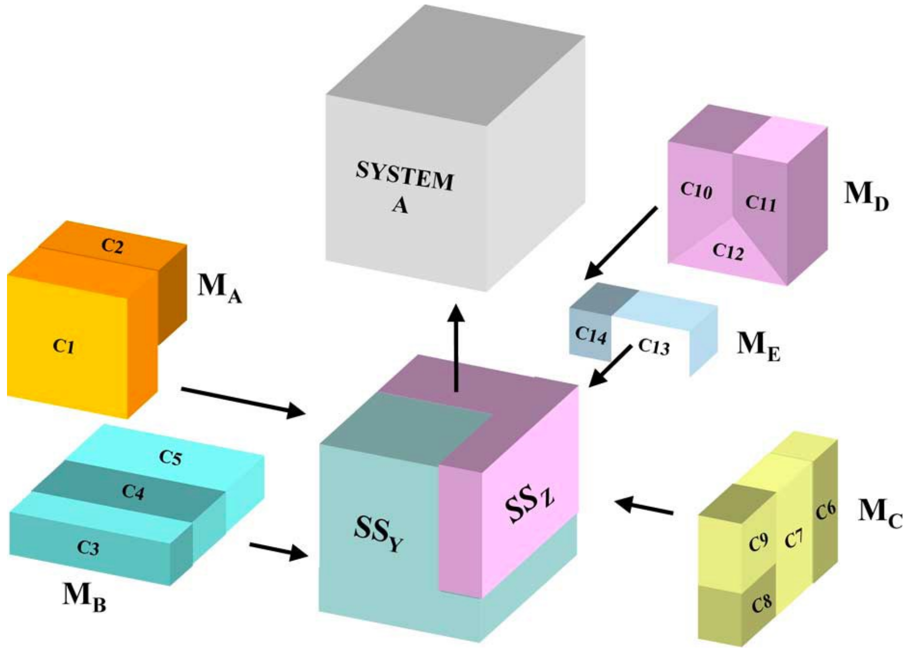


Fig. 3 Schematic definition of modularization

The expression "socio-technical system" is used in order to allow the applicability of this definition to any form of entity available in the business landscape. As the literature shows, the most disparate systems have been considered: physical products (Langlois and Robertson, 1992; Ulrich, 1995), organization (Garud and Kumaraswamy, 1995; Langlois, 2002), processes (Heilala and Voho, 2001; Sanchez and Collins, 2001), services (Voss and Hsuan, 2009; Pekkarinen and Ulkuniemi, 2008), etc. From now on, the socio-technical system will be identified as "the system"

The most general and consistent properties that were identified are summed up in the following list:

- System's architecture breakdown into standard and functional subsystems. It is a general property that can be applied to every kind of system, because this statement only requires the decomposability property, which is attributable to almost anything in nature, and everything one should consider in the different sectors of economy.



From J.H.Mikkola, “Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations” IEEE Transactions on Engineering Management, vol. 54, no. 1, Feb. 2007

Fig. 4 System’s decomposition into subsystems

In Fig. 4, one can notice how the system is made of subsystems, which are a set of modules, which are an assembly of components. The word “component” is not specific to the physical products but it represents any basic unit of a system.

- The optimization of the interfaces. This discriminating characteristic takes into account many different elements: the module boundaries definition, the level of standardization, the communication aspects, and the relationships with outer elements. This characteristic may assume various forms, depending on what the decision maker wants to obtain from the modularization.
- The various impacts on the system’s life cycle. The Fig. 5 illustrates how the different phases of the system’s life cycle are involved in different modularization-related events. Any system is exposed to the modularization’s impacts all along its life cycle, whereas the decisions whether using modularization or not and how to use it, are limited to the first phases of the life cycle.

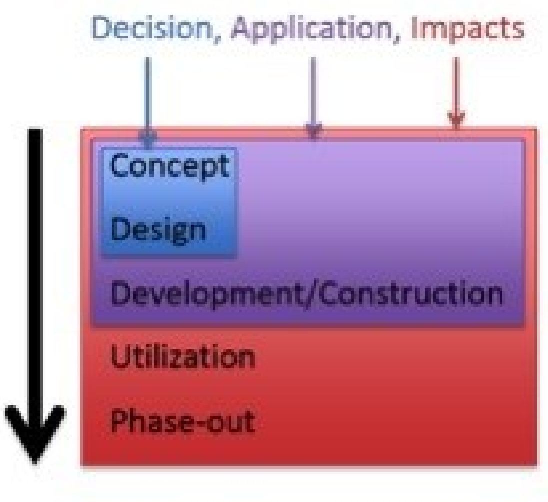


Fig. 5 Life cycle vision of the modularization concept

Some macro-aspects that the researchers described take into account supply chain management decision (Asan et al., 2004; Molina et al., 2005; Matos and Hall, 2007; Brun and Zorzini, 2009), the establishment of modular consortia (Collins et al., 1997), or the platform strategy (Dobrescu and Reich, 2003; Gu et al., 2004; Jose and Tollenaere, 2005; Pekkarinen and Ulkuniemi, 2008).

- The decision making process. This last part sums up what modularization decisions are: first of all, modularization is a choice that drives the system away from integral architectures (Ulrich, 1995; Gu and Sosale, 1999; Takeishi and Fujimoto, 2001; Mikkola, 2003; …); even if it is a matter of degree, this choice pushes the decision makers towards standardization rather than global system's optimization. Once it has been decided to modularize, the essential point is: "where to cut?" (Kusiak and Huang, 1996) This decision is crucial to determine the best system's breakdown.

2. Concept's boundaries

As it has been analyzed in the literature review, the boundaries may be identified following a general scheme that has been represented in Fig. 6, where the aspects have been grouped into general categories, which represent the main scopes the modularization is concerning. These categories are represented from the decision maker's point of view, which permits to picture the general framework of the concept's boundaries in a dual form: to underline that some aspects are out from the decision maker's sphere (external boundaries) and other aspects depend on the behavior of the decision-maker (internal boundaries), the categories are represented in the area in which they belong.

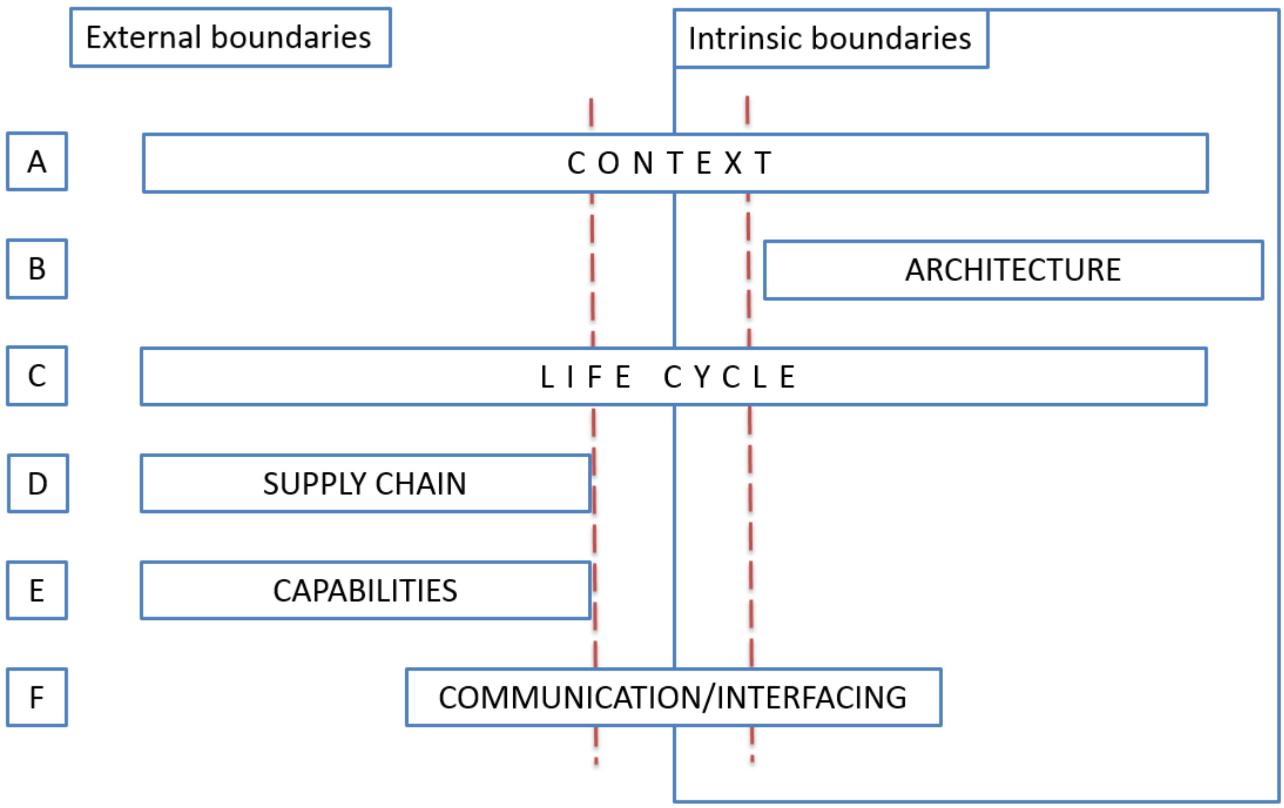


Fig. 6 Modularization's boundaries from the decision maker's point of view

Then, every category is detailed into coded keywords that have been used to investigate the literature during the review, the following schemes are illustrating which are the boundaries of the modularization concept:

External boundaries

Intrinsic boundaries

A

CONTEXT

GLOBAL CONTEXT	MARKET	FIRM
Technological change	Market change	Costs issue
Changing environments	Demand heterogeneity	Existence of hierarchies
Standards/Design rules	Competitive intensity	Variety
Intellectual property	Availability of standards	Technical uncertainties
Inputs heterogeneity	Resources sharing	Decentralized structures
Social systems	Technological restrictions	Tasks specification
Resistance to change	Industry fragmentation	Obsolescence
Different perceptions	Market share	Subsystems autonomy
Government regulation	Mono-product markets	Adapt an existing system
Geographical spread	Market risks	Blurry firm boundaries
Environmental loads	Dynamic markets	Product families
	Market requirements	Competitive performance
		Flexibility

Tab. 40 Context-related boundaries

The context allows the practitioners to differentiate most of the general boundaries of the modularization concept. The global context describes what kind of limit is imposed by the environment, the market level shows how the marketplace creates auto-regulation rules that exclude automatically some aspects from the modularization concept. Then at the firm level, the characteristics that define the concepts boundaries push towards the settlement of the firm structure and of the closest context of the system. Tab. 40 is giving a recap of the main aspects that lead to a limit in the procedure of modularization.

Intrinsic boundaries	
B	**ARCHITECTURE**
Decomposability	Product architecture strategy
Functional requirements	Change-resistant architecture
Easy imitation risks	Over-equipment
Platform architecture	Organizational boundaries
Information structure	Multi-module problems
Optimal configuration	Module selection
Modules characteristics/relationships	Individual parts complex functions
Static/Dynamic architectures	Ill-defined modules
Organizational structure	Functional interaction
Subsystems	Module's components common lifespan
Product families	Bundling
Architectural innovation	Degree of modularity
Components customization	Precise localization of change

Tab. 41 Architecture-related boundaries

The boundaries related to the architecture are bringing up the system's structural characteristics: determining the way the system positions itself within its environment is essential to understand how to configure its architecture. In this case, the modularization boundaries are identified in the ways the decision maker is configuring the "construction" of the modular structure of his system. Tab. 41 lists the areas that lead to the definition of a boundary in the architectural context.

C	External boundaries	LIFE CYCLE	Intrinsic boundaries
Entire life cycle	Product life cycle	Different modularization scenarios	Support activities cost Capital costs
Concept	Opportunity for modularization	Multiple models introduction	"Greenfield" situation Performance degradation
Design		Independent module design, Design for assembly, Adaptive design	Design cost/duration/parameters, R&D costs, Early modules formation
Development Construction	Problems emerge at assembly, Transaction costs, Assembly precision	Reconfigurability, module building takes up space and resources, "Inside" preassembly	Development/Engineering/Set-up/Testing costs, Testability, Production simplification
Utilization	Obsolescence	Redesign, Costs of maintaining modular, Search costs for economies of substitution	Lack of flexibility, O&M costs, Upgradeability, Lean manufacturing
Phase-out		Recyclability, post-life intent, ease of disassembly	Components' reuse

Tab. 42 Life cycle-related boundaries

Identifying limits in life cycle applications is an essential phase of the modularization assessment process. Defining what is leading the modularization to a dead end is absolutely crucial in order to avoid malfunctioning, or even worse consequences. The decision phase (with consists in the concept stage and the design stage) has to take into account everything that is driving the system to failure or malfunctioning in the downstream stages. A deep analysis of the system's life cycle is including a risks analysis that permits the decision maker to judge if the scales hangs more towards modularization. In Tab. 42, every aspect pulled out from the literature is attributed to its phase, and is related to the decision maker's point of view: external boundaries are settled by the global context/environment, while the internal boundaries are regarding what the decision maker himself has to restrict, so that the modularization is feasible.

External boundaries

D	SUPPLY CHAIN	
Suppliers	Customer knowledge Customer's autonomy Cost of returned merchandise	Close and continuous customer contact Highlight capability bottlenecks Value inputs
Buyers	Customer needs Suppliers' switching Supplier selection Specifications negotiation	Reduced technical capabilities when choosing a supplier Make or buy decisions
Both	Outsourcing Supplier-buyer relationships Supply chain coordination Resource chains	Integration with upstream suppliers and downstream customers Physical proximity Mutual dependence, Fidelity

Tab. 43 Supply chain-related boundaries

The supply chain constitutes a fundamental link to the system's achievement. Buyers and suppliers define the dynamics the decision maker has to take into account, when he's designing the system. The possible modularization depends on how the complete supply chain is perceiving this concept. From the buyer's side, there may be a reluctance, because of not knowing what they would face, when the modularization would be realized. From the supplier's side, there might be hesitation, due to the possibility of increased competition with other suppliers. This is why the contracting/negotiations aspect may acquire a greater weight. Tab. 43 lists the elements retrieved in the literature that limit supply chain decisions in order to achieve the system's modularization.

External boundaries

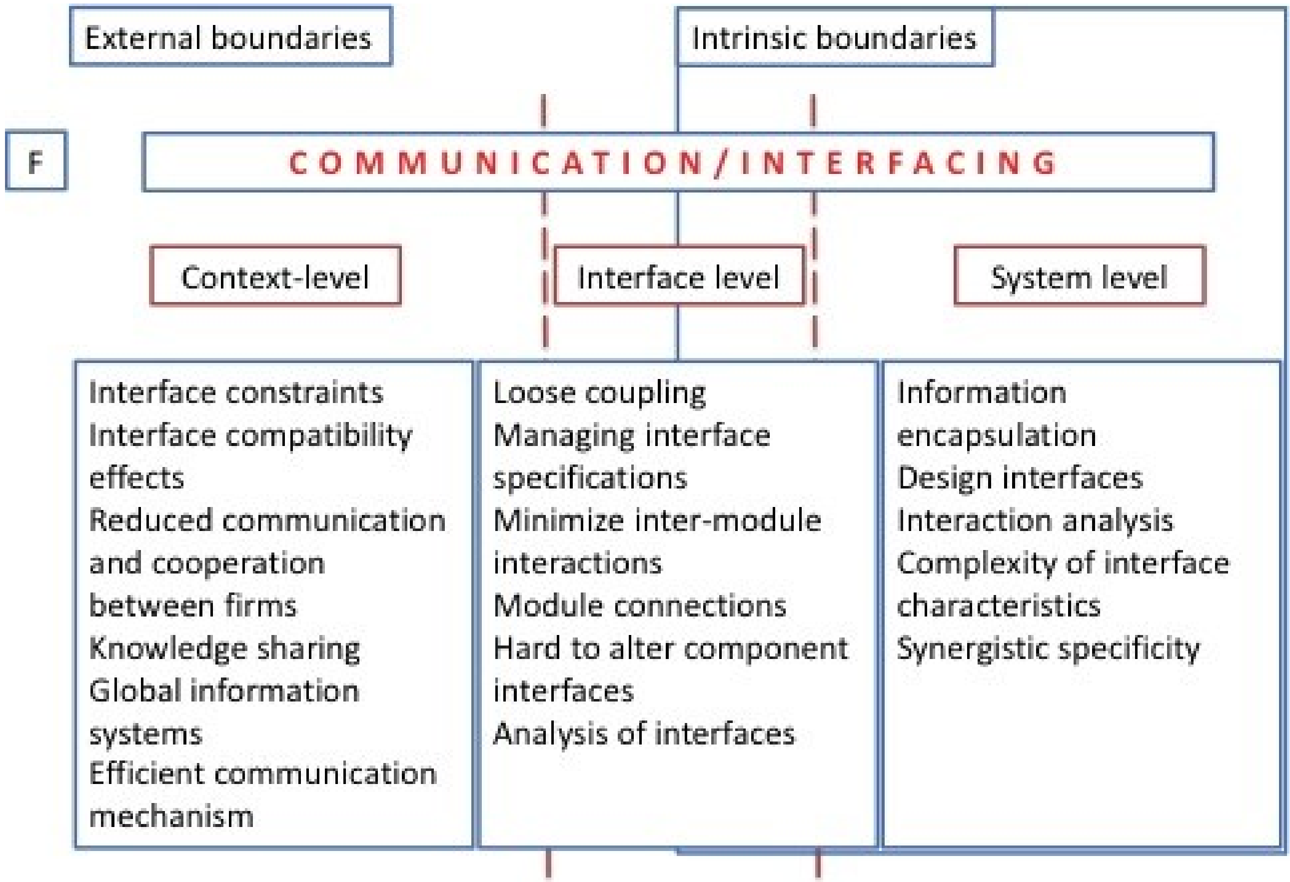
E

C A P A B I L I T I E S

Knowledge (technical, architectural, organizational)	Risk of losing the core business capabilities
Value shifting	Reverse engineering
Level of specialization	Quality
Excessive capability	Skills (planning, engineering, …)
Autonomy	Knowledge loss
Technical complexity	New technologies
Scalability	Multitasking / Coordination
	Dynamic capabilities

Tab. 44 Capabilities-related boundaries

The capabilities that are necessary to implement the modularization are listed in Tab. 44: the boundaries of the concept are represented, in this topic, as a set abilities/risks that the decision maker could need/run into while designing the system's modularization. The managing quality is essential to reach the level of capabilities necessary to cross the boundary that distinguishes modularization from a normal way of designing systems.



Tab. 45 Communication/Interfacing-related boundaries

As in Tab. 40 and Tab. 42, the communication/interfacing related boundaries represented in Tab. 45 are distinguished between those regarding choices that the decision maker handles (intrinsic boundaries, which are identified as all the aspects that are depending on the system's structure) and the other choices that are dictated by the environment (external boundaries, that are assessable among the context – e.g. the market).

Modularization can happen only if specific interrelations between modules are defined, including functionality features and specific communication methods, among the system, the teams and the environment. This obligates the decision maker to set up his organizational strategy in a way that allows the teams and the entire firm to understand each other.

3. Concept's connections with enabling factors and effects

The same concepts that have been developed in the corresponding section of the literature review, have then been retrieved and summarized, to give a complete overview of what kind of connections binds the modularization concept with the enabling factors and effects that might occur during the system's life cycle. The interactions with the concept are represented in Fig. 7:

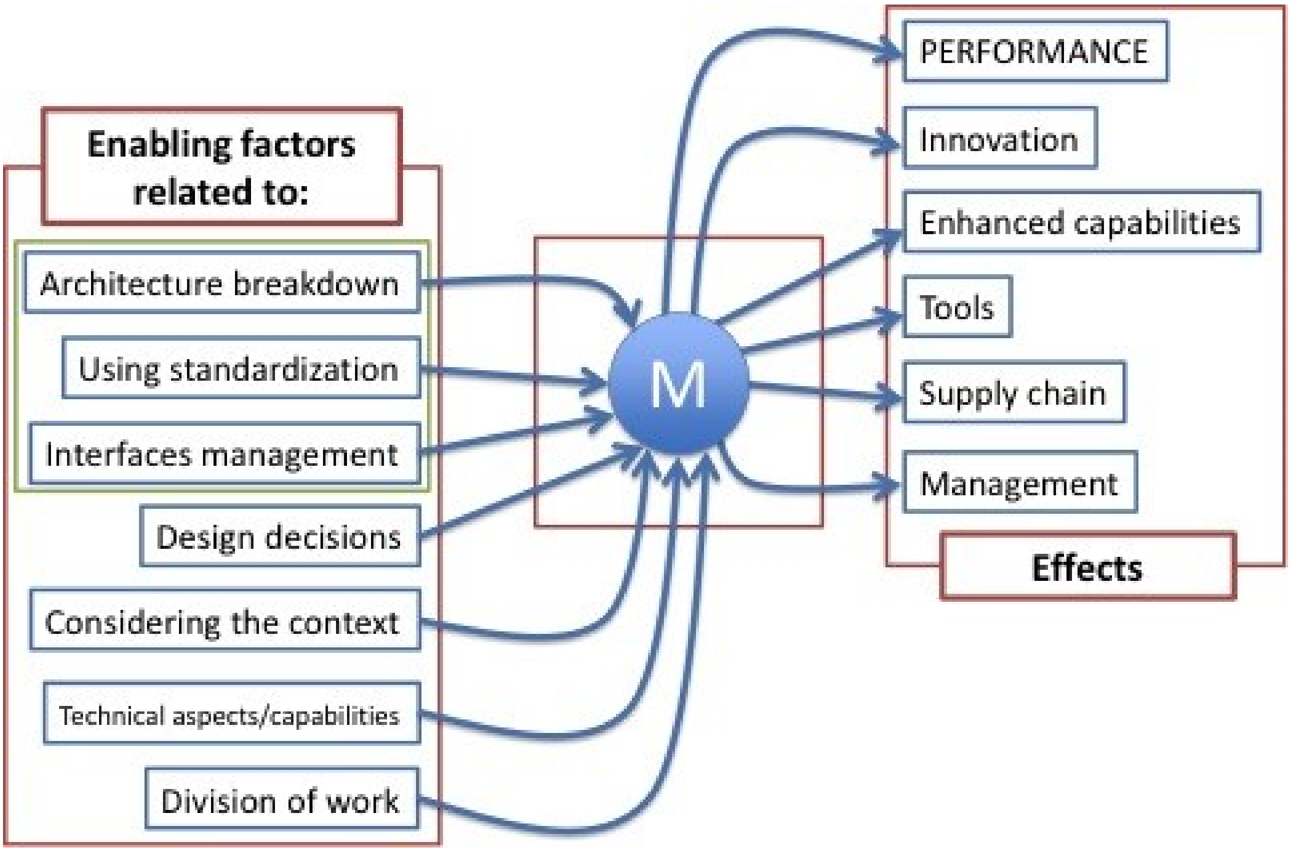
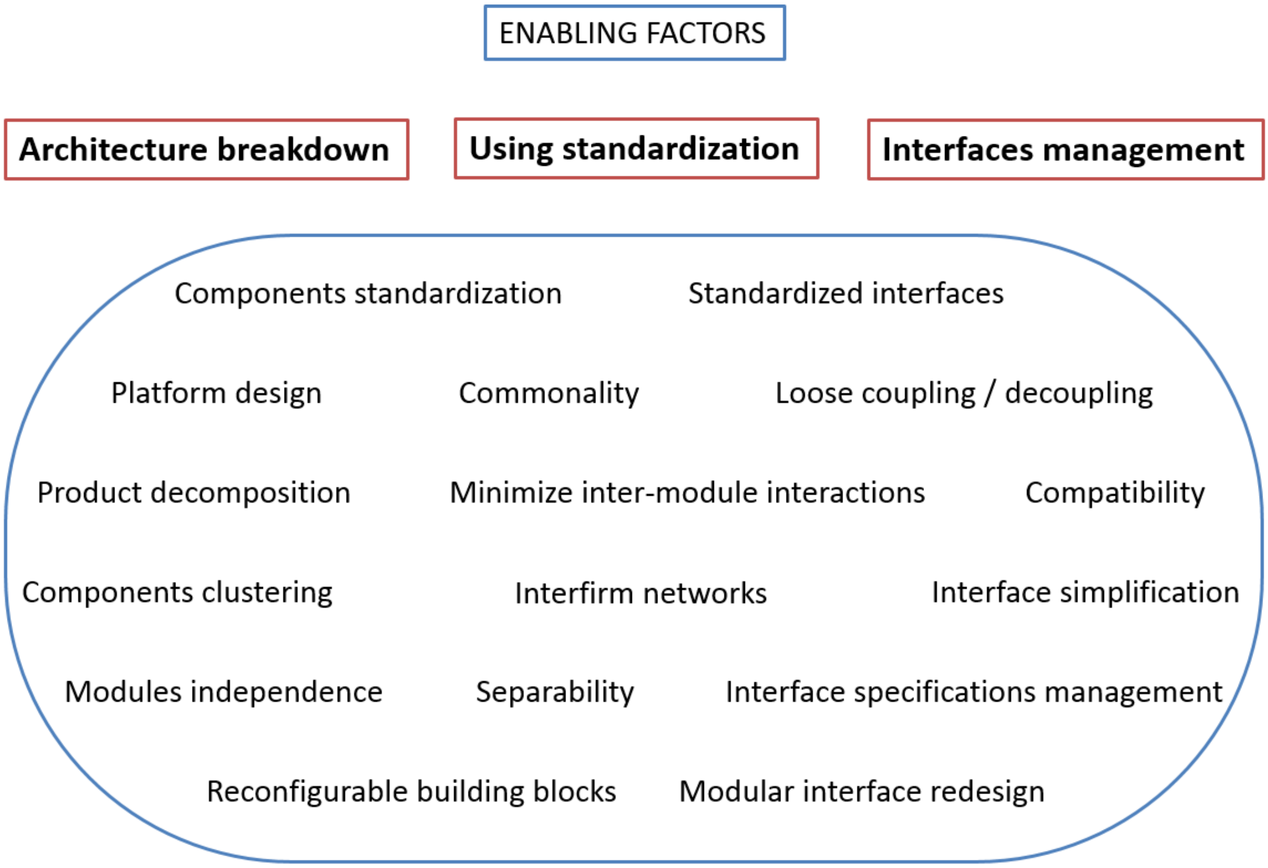


Fig. 7 Concept connections with the enabling factors and the effects

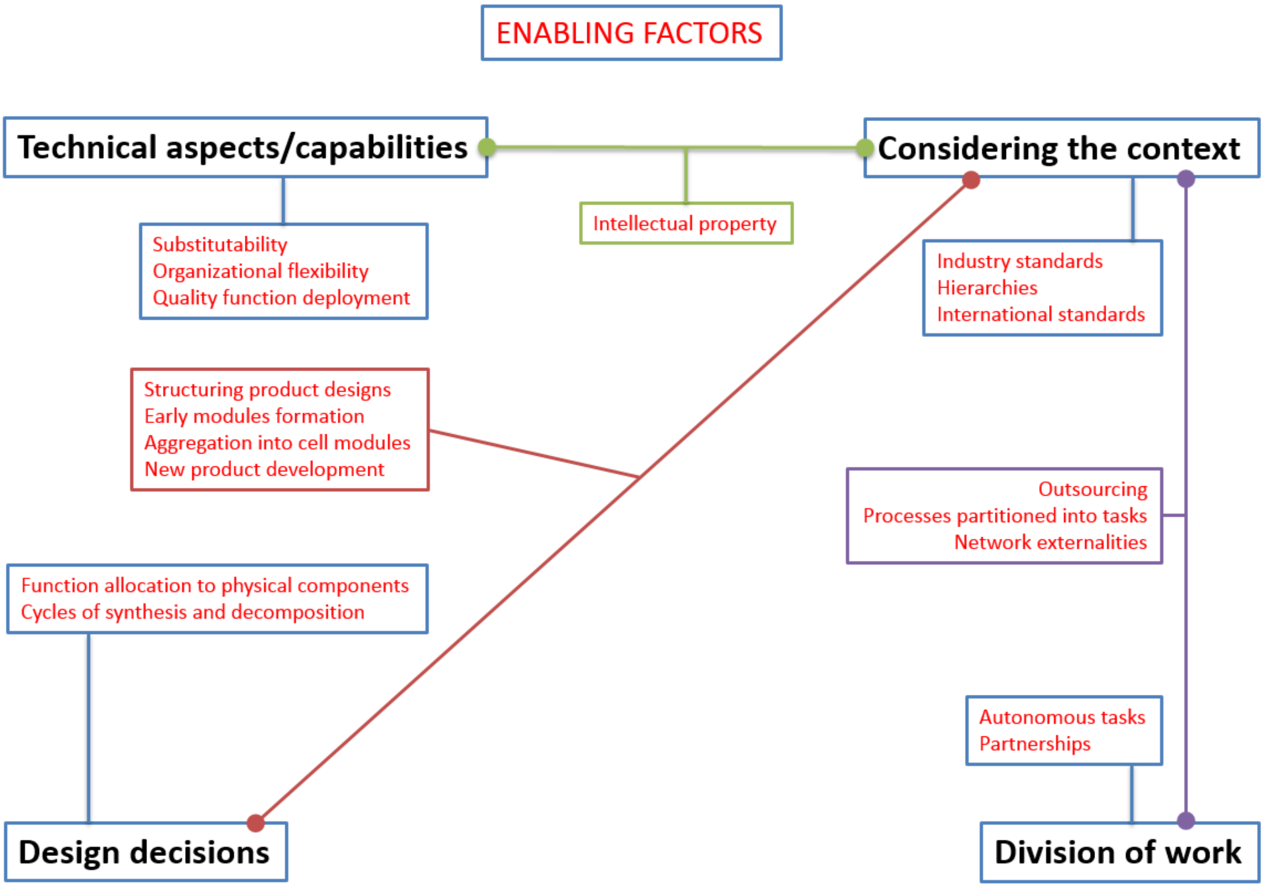
As one can see, the concept of modularization, outside from its boundaries, is connected to the following elements:

- The enabling factors are classified under the properties/characteristics of the concept they are influencing. They are then detailed in Tab. 46 and Tab. 47, represented in two different schemes on purpose, to separate the three main properties a system should specifically define in order to become modularized, from four other aspects that need to be set up well, to enable the modularization.



Tab. 46 The enabling factors having an effect on the basic characteristics of modularization

All the structural elements of modularization are contained in Tab. 46, where one can notice the need of symbiosis among the three properties, which have been defined as essential to the existence of the modularization: if the decision maker manages those three characteristics wisely, the concept and design stages lead the system to the "modular goal". The concept is enabled when those properties come together and the conceptual and design phases are able to establish the complete set of the system's characteristics. The combination of all the concepts present inside Tab. 46 are completely compatible together.



Tab. 47 The enabling factors that have an effect on side aspects of modularization

The other enabling factors described in Tab. 47 are not directly connected to the system functionality, but they contribute to the modularization by facilitating the application of the concept and making it a suitable path to follow in the life cycle perspective. These are practices are allowing the firm and the decision maker to build a solid environment to support the modularized system during its entire life cycle.

- The effects, which represent the link between modularization and every aspect of the system's context, are, again, represented in two different tables, to underline the difference between the effects that impact on the system's performances, represented in Tab. 48, and other effects, represented in Tab. 49, which may occur in a more general context, and could influence other kinds of performance, excluding the modularized one.

EFFECTS: System's performance

Impact on economics
- Savings (e.g. economies of scale/substitution, life cycle costs, transaction costs, initial investment, ...)
- Expenses (e.g. inventory, switching costs, logistics, ...)
- Sales-related (e.g. competitiveness, Sales, ...)
- Tools availability (e.g. cost models, cost characteristics, ...)

Impact on flexibility
- Strategic flexibility
- Interchangeability
- Flexible products designs
- Reusability
- Flexibility in changes
- Agile manufacturing
- Independent modules
- Adaptive potential
- Reconfigurability
- ...

Time- related impacts
- Duration
- Concurrent tasks
- Scheduling
- Obsolescence
- Job turnaround time
- Switching time
- ...

Risks related impacts
- Overall risks
- Inventory risk
- Radical innovation
- Opportunism
- Manufacturing process stabilization
- Suppliers responsibility
- Technical uncertainties
- Uncertainty
- Suppliers choice
- ...

Impact on quality
- Testability
- Specialization
- Value for consumers
- Serviceability
- Innovation diffusion
- Robustness
- Critical components identification
- Design optimization
- Product features
- Information flow
- ...

Impact on efficiency
- Speed to market
- Easy-to-install components
- Autonomy
- Productivity
- Inventory
- Waste
- Easier manufacturing
- Energy efficiency
- Collaborations
- Scalable capacities
- ...

Impact on variety
- Economies of scope
- Component variety
- Configuration options
- Mixing & matching
- Variety
- Different materials
- Differentiation
- Diversity
- Service variety
- ...

Customization impact
- Component customization
- Service customization
- ...

Tab. 48 The effects on the system's performance

Tab. 48 shows that the impacts on system's performance, which are popping up from literature, are exalting the use of modularization. Some of the effects described during the literature review are, however, in contradiction (e.g. more configuration options and easier manufacturing, or less obsolescence and more innovation diffusion).

EFFECTS: **Other Effects**

Capabilities availability

Human resources related
- Coordination
- Autonomy
- Increased specialization
- Increasingly complex technology handling
- Serviceability
- Job turnarounds
- …

Knowledge related
- Knowledge transfer
- Intellectual reuse
- Joint development ventures
- Lean manufacturing
- …

Flexibility
- Adaptation
- Versatility
- Coping with changing markets
- Supply chain reconfiguration
- Scalable capacity
- Substitutability
- …

Sustainability related
- Reusability
- Waste reduction
- …

Modeling and decision support tools and practices

- Design structure matrix
- Sensitivity analysis
- Cost model
- Genetics algorithm
- Rewards
- Clustering methods
- Software tools
- Strategic learning
- Atomic theory
- Computer aided design
- Cost penalty method
- Failure rate model
- Fuzzy logic approach
- Holonic product design
- Integer programming
- Service modularity function
- Strategic drivers
- Task structure matrix
- Weighted goal programming
- …

Innovation practices

- Architectural innovation
- Incremental innovation
- Radical innovation
- Technological change
- Individual module change
- Interchangeability
- Derived product models
- Module variations
- Upgrades
- Add-ons
- Adaptations
- IT advances
- Innovation diffusion
- Interfirm learning
- Changeability
- Components' improvement
- Learning-by-leveraging
- Learning-by-planning
- …

Supply chain practices

- Supplier-buyer relationships
- Inventory management
- Assembly simplicity
- Contract manufacturing
- Modular assembly into customer sites
- Connected supplier production lines
- Interfirm coordination
- Customer management
- Material handling mgmt.
- Quality control management
- …

Organizational design and practices

- Specialized firm
- Less management over the design process
- Centralized coordination and control
- Organizational design reconfiguration
- Embedded coordination
- Innovation
- Stabilize processes
- …

Strategic management practices

- Alliance formation
- Interfaces management
- Strategic learning
- Competitive strategies
- Financial arrangements
- Leverage Investments
- Strategic drivers
- …

Tab. 49 The other effects on the system's performance

One can notice that the modularization obviously fosters the induction of new or usually unused capabilities, which are available to the firm's decision maker in the future. Modeling and decision support tools and practices are the instruments that have been used within the modularization, which though are general instruments that may be used in any kind of socio-technical context. Most of the practices regarding innovation, supply chain, organization and strategic management are highlighting the most general aspects that a manager could take advantage of, in any socio-technical context. These areas of competence have not to be neglected, in order to adopt the best available modularization process.

VI. Discussion

The definitions given by researchers have been reviewed (a list of them is given in IV. 4.), listing every flaw they were containing. The objective regarding the generalization of the concept has been reached by building the concept's ontology.

There is still to define the link between modularization and modularity. Miller and Elgard (1998) give a satisfying definition of the connection between the two concepts:

> *"Modularity is an attribute of a system related to structure and functionality. […] Modularization is the activity in which the structuring in modules takes place."*

To reach a condition that would give the opportunity for modularization, modularity properties have to be defined by the designers: at least one component of the system has to possess modularity characteristics to define the process as a modularization. Thereafter, the system's modularization is converted into a standard procedure, which could be repeated in other similar circumstances. This way, the method may give rise to modular expansions of the system within its environment. (Fig. 8)

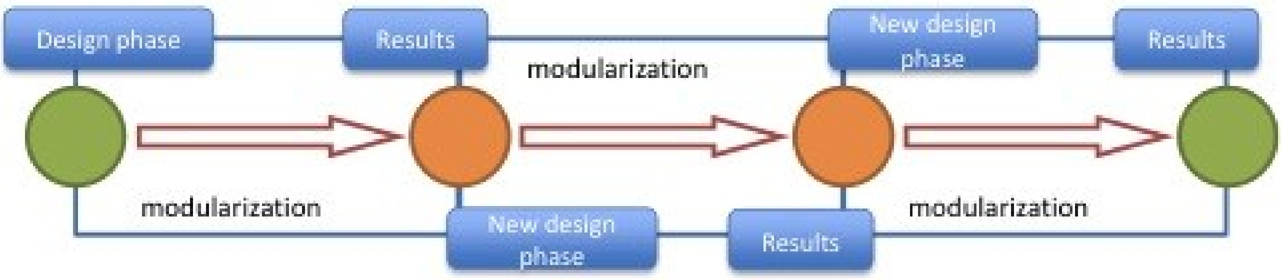


Fig. 8 Sequence of modularizations

As it has been shown in the ontology, the concept can be expressed as a top-down decomposition of the entire system, instead of a bottom-up assembly (e.g. He and Kusiak, 1997; Fujita, 2002) of components into modules. A fundamental aspect of modularization is that the decision maker has to be free to divide the system into the chunks as he better likes. Therefore, he needs to face the entire framework of the breakdown possibilities, to be able to employ a complete modularization process, which involves the assessment of everything that may happen to the modularized system on various fronts (e.g. on life cycle in Umeda et al. (2009), supply chain in Matos and Hall (2007), firm's organization in Hoetker (2006), workforce in Takeishi and Fujimoto (2001), knowledge in Brusoni and Prencipe (2001), etc.)

These fronts are already described in scientific literature, but they are fragmented due to the fact that researchers utilize them in their papers, that typically focus on a specific area of interest. From this examination, while most of the modularization attributes may be retained as exhaustive, some specific context's characteristics have not been taken into account (maybe because they are less related to the manufacturing industry):

- The meteorological aspect, which influences the design of the socio-technical system. For example, a power plant would have different characteristics, if the location was tropical rather than if it was polar.
- The geographical aspect that literature mentions barely. This context's characteristic is leading to diverse areas of competence: the political situation, the legislative context, and other local issues may push towards certain decisions, which would interfere in the modularization process.
- The infrastructural aspect is playing a major role in the modularization decisions, especially regarding the development stage
- The social aspects as well are essential to be considered (e.g. the availability of workforce)
- …

Those characteristics are arising from major issues designers run into in the project engineering context (e.g. plant building, events management, construction industry, etc.). Modularization could resolve the problems emerging from those characteristics.

Determining the tradeoff between the convenience of breaking down the system into little and manageable chunks (e.g. Mikkola and Gassmann, 2003) and the creation of a large number of interfaces (e.g. Gershenson et al., 2004) is still an unresolved issue (see Fig. 9), which is too specific to the single cases to be part of such a generic ontology of the modularization.

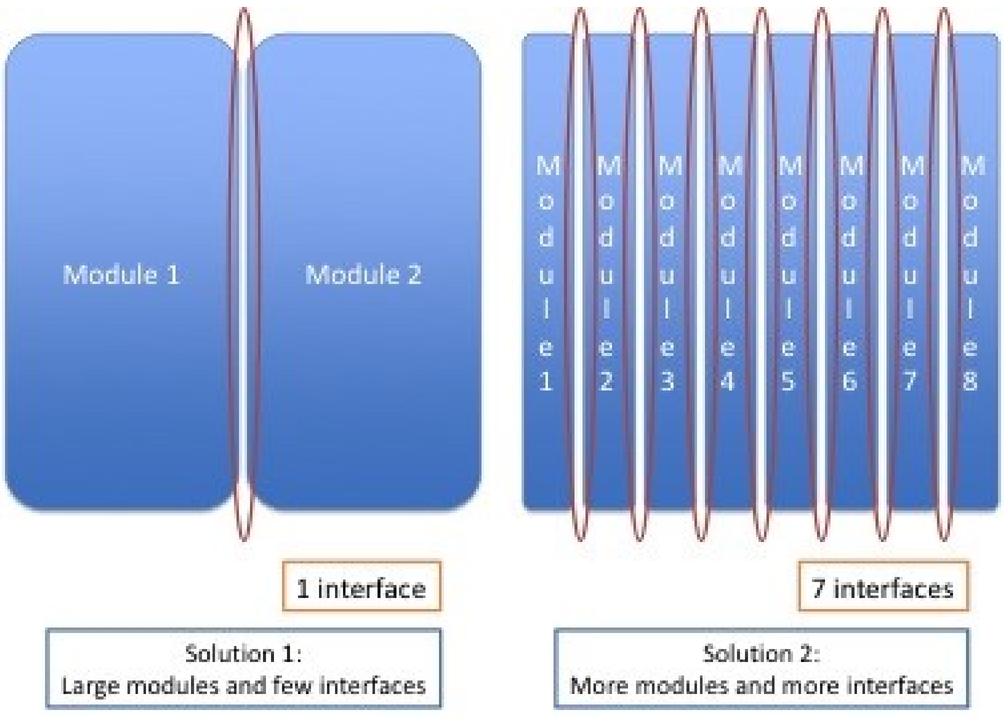
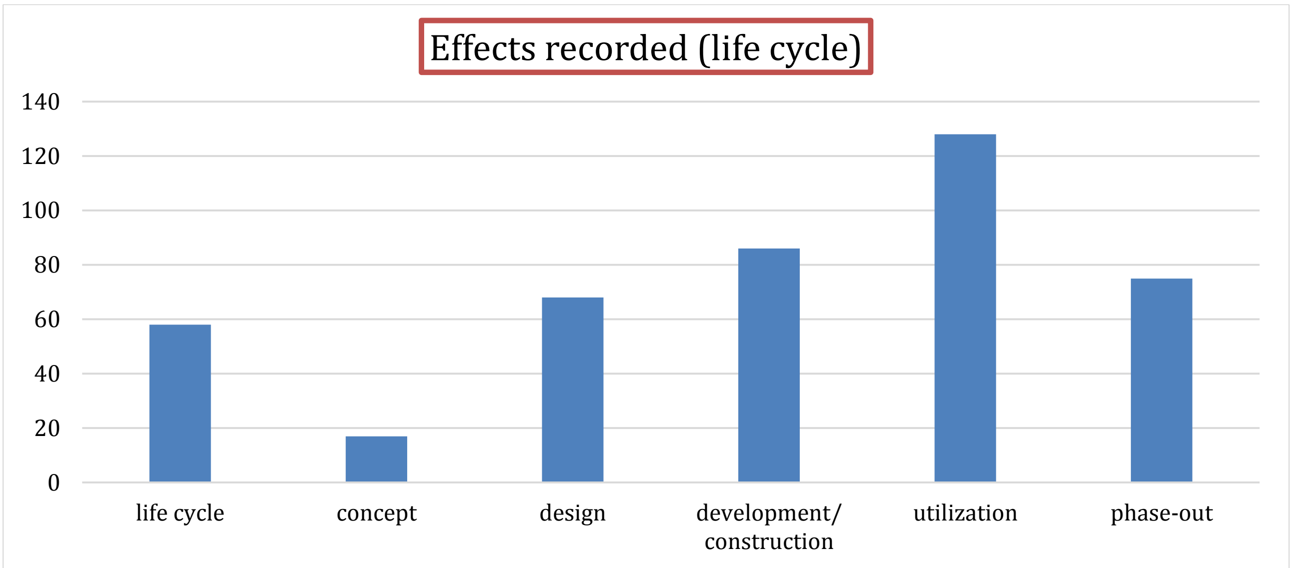


Fig. 9 System's division into modules

Historically, this decision does not depend from general evaluations, like the life cycle assessment, but it comes from the evaluation of the manufacturing/construction of the physical product (which is traditionally the area of implementation of modularization). That is to say, following the assembly order or the convenience for manufacturing, the product is put together from subsystems, not considering any life cycle aspect except for construction/manufacturing aspects, which may be identified generally as the development phase.

The decision maker should evaluate, considering the previously cited fronts (life cycle, supply chain, firm's organization, workforce, etc.), which level of modularization is the more convenient for his case. This decision should be taken during the concept stage, when the most generic aspects about the potentially modularized system are still undefined.

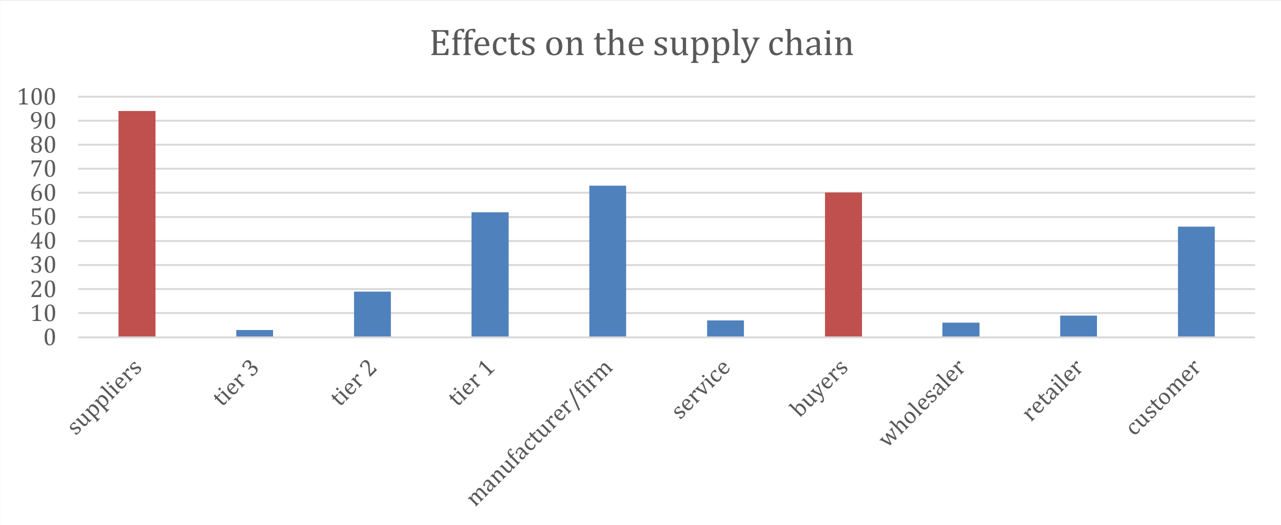
In Diag. 11, one can observe the trend of the publications divided into the effects recorded in the diverse life cycle phases, which clearly show a major interest of the impacts modularization can originate during the utilization phase:



Diag. 11 Effects recorded on the different life cycle phases

Modularization can play a leading role in the phase-out stage by improving practices like the reuse, the easy recycling, etc. It leads to a life cycle vision, which consists in the evaluation of the modularity characteristics (that is to say the system's inner properties induced by modularization) and its impact over every single stage of the system's life cycle.

Diag. 12 shows the papers' count of the effects on the supply chain. Suppliers are cited more than buyers, which essentially are identified in literature as customers. One can notice that most of the papers about the effects are regarding first tier suppliers, the manufacturer/firm and the customers. Thus, there has been a growing interest for second tier suppliers (e.g. Fixson et al., 2005) which is more and more involved in the modularization as the first tier supplier is gaining more important responsibilities.



Diag. 12 Effects recorded on the supply chain

The decision making moment is crucial to establish what is influencing the modularized system during its life cycle (e.g. Mehrabi et al., 2000). Every decision leads to a chain of events that impacts on many aspects of the system's properties and surroundings (e.g. a change of the module's interface has an impact on both modules that are connected by this interface. But are the effects limited to both modules or are they impacting other elements of the system? What are the effects on the system's performance?).

Since the modularization is a design decision, there should be a complete life cycle assessment, in order to define most of the consequences the action of modularizing the system brings up. Fig. 10 illustrates how the concept of modularization is described in the literature, and how the vision of the phenomenon should be:

- The evaluation of only a few elements (Fig. 10a) may lead to a situation where designers, after attributing certain characteristics of modularity to the system (that are determined through the superficial analysis of the chain of effects), face some architectural problems that require addition effort and resources from the firm. These hitches are mainly due to lack of in-depth analysis.
- Instead of that, every effect, and second order effect (and so on, like in Fig. 10b) could be analyzed in order to prevent the system from undesired events. This could even lead to the opportunity of employing a deeper degree of modularization.

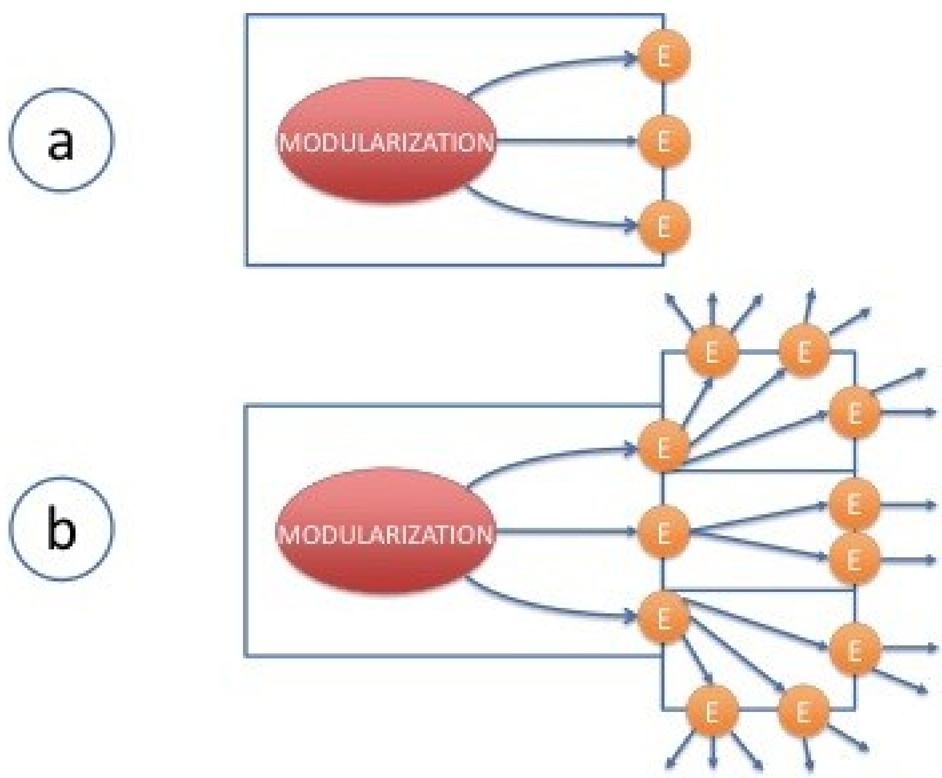


Fig. 10 Differences between (a) what is described by the literature, and (b) what should happen when the modularization is adopted

This point of view allows to highlight that any modification to the modularized system leads the modules and the subsystems to changes that may compromise the optimization of the whole system. For example, modular innovation (e.g. Galunic and Eisenhardt, 2001; Sosa et al., 2004) is perceived as a competitive advantage of modularization, compared to a non-modularized system, but these alterations of the modules may force the designers to reconsider the complete system architecture, because of effects that they may have neglected during the conceptual phase.

The mechanism of modularization has to be studied globally, considering the complex chain of cascading effects, to be able to define the impact comprehensively undergone by the system and the firm. Once the impacts are known, a decision about modularizing or not modularizing can be taken. For example, design decisions that impact on system's life cycle stages ("Decision" box in Fig. 11) have to be determined after achieving an in-depth analysis of the downstream stages (development, utilization, and phase-out), which correspond to the box "Action" represented in Fig. 11. Therefore, knowing what happens after the decision helps to take the best decision.

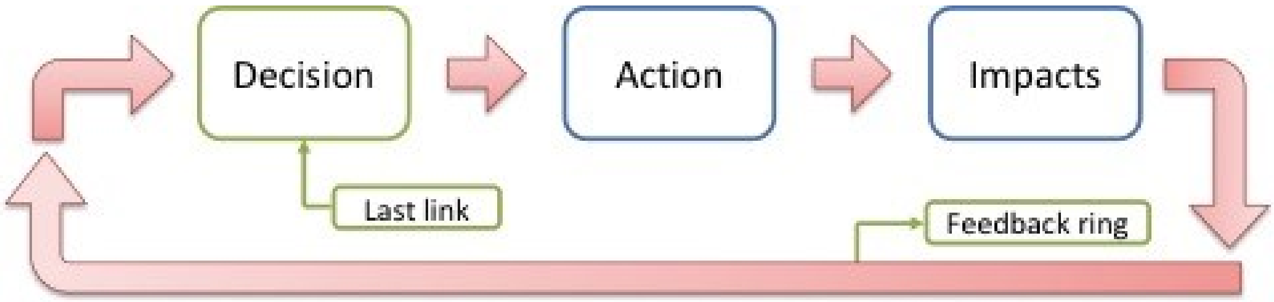


Fig. 11 General decision procedure regarding any phenomenon

The essential question could be why should a firm decide to employ the modularization on its systems? As it has been discussed in IV. 3. b., the kinds of performance a firm may require from its modularized system are belonging to the following macro-categories:

- Economic
- Flexibility
- Time
- Risks
- Quality
- Efficiency
- Variety
- Customization

The more modularization is employed, the more designers get used to deal with design decisions' consequences, and the less the system is causing negative effects to the firm. The decomposition of any system in modules requires experience and knowledge, which are acquired only by utilizing it.

Further research

As it has been underlined in the open issues of the literature review, the following question has still to be answered: "where do I cut a system to accomplish the modularization? And how will the selected cut be identified as the best way to decompose the system?" This leads to the tradeoff evaluation, between a deeply decomposed system and a system with the fewer number of interfaces.

Furthermore, the coverage of the sectors of economy is not complete and the progress obtained in the area of physical products has to be enlarged and deepened in diverse uncovered sectors (there are plenty of examples among the tertiary and the quaternary sector). The in-depth studies that have been performed about physical products have to be used as a basis to investigate the effects of modularization, for example on intangible objects and non-assembled artifacts. At the same time, the knowledge about the contexts' characteristics that are listed during the discussion should be further investigated.

From what the ontology provided (i.e. the new, enlarged definition of the concept, its boundaries and the enabling factors and the effects of it within its context), researchers are able to investigate the modularization mechanisms (that is to say, the chain of events that the action of modularizing brings up), the causes and effects of every single consequence that modularization is occasioning: every aspect described in IV. 3. b. has to be assessed, and the mediating factors have to be investigated (some effects noticed during the literature review were in contradiction, this incoherence has to be clarified).

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Appendix A – List of the journals

List of the journals
Academy of Management Journal
Academy of Management Review
AIIE Transactions (American Institute of Industrial Engineers)
American Society of Mechanical Engineers, Design Engineering Division (Publication)
Assembly Automation
Business Process Management Journal
CAD Computer Aided Design
Chemical Engineering & Technology
Chemical Engineering and Processing: Process Intensification
Chemie Ingenieur Technik
Chimica Oggi
CIRP Annals - Manufacturing Technology
Computer Aided Chemical Engineering
Computers in Industry
Concurrent Engineering Research and Applications
Decision Sciences
Design Studies
Economics Letters (not available because polimi bought the review from 1995)
Energy Economics
European Journal of Operational Research
European Journal of Political Economy
European Journal of Purchasing and Supply Management
European Management Journal
Expert Systems with Applications
Harvard Business Review
IEEE Robotics and Automation Magazine
IEEE Spectrum
IEEE Transactions on Components Packaging and Manufacturing Technology Part A
IEEE transactions on components, packaging and manufacturing technology. Part C. Manufacturing

IEEE Transactions on Engineering Management
IEEE Transactions on Knowledge and Data Engineering
IEEE Transactions on Robotics
IEEE Transactions on Robotics and Automation
IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.
IEEE/ASME Transactions on Mechatronics
IIE Transactions (Institute of Industrial Engineers)
Industrial and Corporate Change
Industry and innovation
Integrated Manufacturing Systems
Interfaces
International Journal of Advanced Manufacturing Technology
International Journal of Agile Manufacturing
International Journal of Automotive Technology and Management
International Journal of Computer Integrated Manufacturing
International Journal of Industrial Organization
International Journal of Life Cycle Assessment
International Journal of Logistics Management
International Journal of Operations & Production Management
International Journal of Physical Distribution and Logistics Management
International Journal of Production Economics
International Journal of Technology Management
Journal of Cleaner Production
Journal of Economic Behavior and Organization
Journal of Engineering Design
Journal of Integrated Design and Process Science
Journal of Intelligent Manufacturing
Journal of International Business Studies
Journal of Loss Prevention in the Process Industries
Journal of Manufacturing Systems
Journal of Manufacturing Technology Management

Journal of Marketing
Journal of Mechanical Design - Transactions of the ASME
Journal of Operations Management
Journal of Organizational Computing and Electronic Commerce
Journal of Product Innovation Management
Journal of Robotic Systems
Long Range Planning
Management Science
MIT Sloan Management Review
Nuclear engineering and design
Organization Science
Organization Studies
Power Electronics Technology
Proceedings of the ASME Design Engineering Technical Conference
Production Planning and Control
Progress in Nuclear Energy
R and D Management
RAND Journal of Economics
Renewable and Sustainable Energy Reviews
Research in Engineering Design - Theory, Applications, and Concurrent Engineering
Research Policy
Robotics and Computer-Integrated Manufacturing
Strategic Management Journal
Technovation

Tab. 50 List of the journals

Appendix B – Attached documents

The attached file contains two documents:

- The literature collection, with some general information about every paper;
- The table containing the papers' keywords, divided into the different categories used to define the concept, its boundaries and its effects;