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Assessing Product Development Performance Analyzing the Information Flows Structure using Social Network Analysis Measurements

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Abstract**—**This paper presents an approach useful to analyze the performance of a product development process. The approach is based on the assumption that understanding in depth the web of information and knowledge flows during product development can help gain insights to as how to improve the whole process. Particularly, the chain of tasks is modelled using the Dependency Structure Matrix (DSM) tool, while the nature of the information and knowledge flows coordinating tasks were the primary focus of the study. Metrics from the Social Network Analysis (SNA) are calculated to investigate properties of the specific product development process.

The analysis was supported by the continuous feedback from technical managers and engineers involved in the subsystem development. A questionnaire was developed and administered to collect data. Most of the data were collected using measurement scales designed for the purpose. Results relative to the application of the approach to the development of the climate system of a new car model developed by a large Italian car manufacturer are presented. This paper contributes to literature as it takes into account both ambiguity and uncertainty amounts to assess information flow quality. Furthermore, it explores how the differences of organizational units culture and experience affect people perception of development process complexity and structure.

Keywords**—**network analysis; product development; information flow; ambiguity; uncertainty; DSM.

I. BACKGROUND

LITERATURE on the new product development process emphasizes how decision-making is a critical management lever for achieving the product success [17], [20], [29]. Organizations make decisions regarding product variety, standardization and customization thus shaping their product strategy by defining product architecture, platforms, modularization and standardization degree and typology [3], [28], [29]. Making decisions early in the product development process when much is still unknown and uncertain can positively influence performance if the forecast is correct, while postponing decisions to downstream phases when information and opportunities are more certain may negatively impact on performance [31]. A large part of critical decisions during the product development process lifecycle relate to issues such as technical problem-solving, supplier involvement, task partitioning, cost management, and product structure. This latter has a major role in shaping the product development model adopted by the organization and its performance. Indeed, the choice of a specific product structure has an impact on product development performance, development phasing and organization, organization relationship with its suppliers, R&D and operations globalization, usually affecting time, costs, product quality and variety.

The choice of the product structure also impacts on how the product development process is organized (i.e., the list of tasks that are necessary to develop the product having a defined structure, the selection of tasks that should be implemented within the organization or outside by external suppliers, etc.). Finally, the performance of the new product development process is strongly affected by the way the component tasks are interconnected and coordinated. Scholars that investigated the product development process from an information management perspective underlined how the exchange of technical and managerial information and knowledge strongly affects decision-making, product development performance and risk [3], [13], [28]. Developing a new product often requires the completion of hundreds of closely coupled tasks, grouped into phases and stages, through which the concept, configuration and other technical details of the product are generated, narrowed, and finalized [18]. Further, product development frequently implies rework and refinement to account for unexpected failure to meet target specifications or new more useful information and knowledge generated from downstream tasks after completing an expected iteration, thus modifying previously made decisions [26]. The couplings and dependencies between product development phases need the exchange of product-specific information between development teams – i.e., the transfer of customer preferences from the marketing group to the design group that allows designers to generate and finalize the product concept and detailed design charts and drawings. Reference [11] shows, for instance, that the adoption of an overlapping approach of tasks without a high level of inter-functional team use (and henceforth, communication and exchange of information) may lead to scarce performance.

Understanding in depth the web of information and knowledge flows during product development can help gain insights to as how to improve the whole process, i.e. how to

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streamline it, identify potential iterations, and effective coordination mechanisms. This paper uses Social Network Analysis (SNA) to investigate the structure of information flows and the Dependency Structure Matrix (DSM) to model task interdependency in terms of information and knowledge exchange between interacting tasks during new product development [4], [5]. The case of the climate system developed for a new car manufactured by a large Italian car OEM is investigated. Social Networks metrics were calculated to analyze the information flow characters [25].

This paper contributes to literature as it takes into account both ambiguity and uncertainty amounts to assess information flow quality. Furthermore, it explores how the differences of organizational units culture and experience affect people perception of development process complexity and structure.

II. THE ANALYSIS OF THE INFORMATION FLOW STRUCTURE

The study adopts a research approach that is similar to approaches already adopted in the literature [5], [6], [7], [23] [24], [32]. The formal and informal communication exchange between tasks during new product development is captured through the Dependency Structure Matrix (DSM) representation [5], while the properties of the information and knowledge flow structure are explored calculating metrics typical of social network analysis (SNA) [15].

A. The Dependency Structure Matrix

A DSM is a square matrix with corresponding rows and columns. The tasks are represented in the diagonal cells. Off-diagonal cells indicate the dependency of one process element or task on another. Reading down a column shows input sources, while reading across a row reveals output receivers. A task is the information-knowledge processing unit that receives information and knowledge from other tasks (preceding or coming after) and transforms it into new information and knowledge (or in a different form of it) that is transferred to subsequent tasks. In a time-based DSM, tasks are listed from upper left to lower right in a roughly temporal order. Upstream tasks in a process precede downstream activities. Superdiagonal matrix entries indicate feedforward information; vice versa, subdiagonal entries show feedback (i.e., some iteration and rework activity in the development process). In the matrix, information flows in a clockwise direction. If tasks in rows (and corresponding columns) have no direct interfaces, they are independent, entries in the matrix will be zero or empty. If, on the other hand, both entries are filled, this indicates a two-way interdependency or coupling between the activities.

The development of the DSM required a significant effort from experts to identify and assess inter-task dependency in terms of information attributes. It was built by interviewing people knowledgeable about each task of the process and eliciting their expert opinions about a number of questions (i.e., people perception about information and knowledge quality in the process task). Two dimensions of the information and knowledge flow were privileged: a) ambiguity perceived by individuals who are unable to interpret the meaning of facts and actions, or make a choice when there are multiple redundant interpretations about the variables of interest to the design problem [9], [10], and b) uncertainty perceived by individuals when they lack complete information to make a decision or carry on specific tasks [14], [22].

B. The Social Network Analysis (SNA)

Social network analysis is a useful way to understand and analyze systems in which the most important characteristics are their individual components (nodes) and the connections between these components [15], [21]. Making the assumption that the way the components of an organization communicate to each other affects some important features of the organization, it has proved particularly effective in framing and understanding how communication and integration occurs between individuals and groups within organizations when they carry on innovation and/or knowledge and technology transfer [1], [16], [27], [30]. Social network analysis (SNA) allows to map and measure relationships and information and knowledge flows between people and units within an organization using concepts, visualization techniques, and mathematical tools provided by the graph theory [2], [15].

C. Measurements of product development performance

Centrality is one of the concept that social network analysis uses to investigate the properties of a network. Measures of centrality provide a rough indication of the “power” or the “structural importance” of a node to control action based on how well it "connects" the network. Two measurements of centrality are particularly important, degree centrality and betweenness [12].

The Freeman centrality degree. Degree centrality is defined as the number of direct ties that a given node has [12]. The degree of node *i* is given by:

$$d_i = \sum_j a_{ij} \qquad (1)$$

The most central node is the one with the greatest number of connections. If the network is directed (meaning that connections have directions), then we usually define two separate measures of degree centrality, namely indegree and outdegree. Indegree (reception) is a count of the number of ties directed towards the node (i.e., the number of interactions it receives), and outdegree (emission) is the number of ties that the node directs to others (i.e., the number of interactions it originates).

For a weighted network, the outdegree of a node is the sum of all values corresponding to the edges incident from it divided by the number of all other nodes in the network, while the indegree of a node is the sum of all values corresponding to the edges incident to it divided by the number of all other nodes in the network. At the network level, centrality measures the degree of uniformity/non uniformity in the distribution of information within the networked product development process, thus providing a measure of informational entropy in the process. When the Freeman’s centralization index increases, useful information to solve technical problems tends to be localized within a reduced number of tasks.

Betweenness centrality. Betweenness centrality measurement is based on the number of shortest paths between every pair of other group nodes on which the focal node lies. It may be defined loosely as the number of times that a node needs a given node to reach another node. In mathematical terms it is defined as

$$b_k = \sum_{i,j} \frac{g_{ikj}}{g_{ij}} \tag{2}$$

where g_{ij} is the number of shortest paths from node i to node j, and g_{ikj} is the number of shortest paths from i to j that pass through k. The purpose of the denominator is to provide a weighting system so that node k is given a full centrality point only when it lies along the only shortest path between i and j.

In a product development network, betweenness centrality measures the extent to which certain tasks are able to control the communication flows coordinating other pairs of tasks. It quantifies the extent to which information exchange between the other pairs of tasks would be reduced if the task were removed from the process. This index is a useful measure of potential control over communication and sources and the contribution of a task to all information flows, assuming that influence comes from being an intermediary [12]. In other words, betweeness centrality measures the relevance of a task of the process in transmitting information to other process tasks. In other words, tasks having high betweenness centrality may be considered to have more power than others to control, coordinate, and influence a given network.

III. THE CASE STUDY

Data used for the study relate to the development process of a new car climate system. The car climate control system performs two basic functions, passenger compartment heating and cooling. The system is composed of two subsystems that contain several functional components, the climate control subsystem, and the compressor/conditioner subsystem. Fig. 1 shows the typical components of a car climatic system.

Data relative to the development process of the car climate system were collected from formal documents and face-to-face expert interviews in the "Methodologies", "Packaging", and "Climate System" Units of the Product&Process Engineering (P&PE) Department. These units intensively interact during the development of the climatic system. A 5 level anchor-grid scale was developed to collect qualitative judgments. Three sub-processes (Target Setting, Design, Prototype&Test) were identified as parts of the overall process, while 40 tasks were considered as being the most relevant of the process and selected to build the DSM.

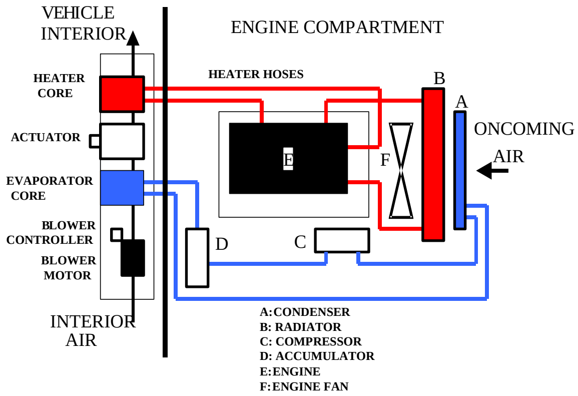

Fig. 1 The components of a car climate control system

The company Product Development Process (PDP) includes several activities: a) *Objective Definition*, in which the objectives of the development process are defined; b) *Style*, in which different models are defined according to the choice of car interiors (facia, instruments, upholstery, etc.); c) *Under-body Planning and Development*, in which the car platform is designed and developed; d) *Product Frame*, in which the components of the car are designed based on the existing ones belonging to old models; e) *Product and Market Location*, in which different car models and versions to be launched in the market are selected; f) *Step Cad Development*, in which design and development of the car is made; g) *Virtual Prototype* and *Physical Prototype* are sub-processes in which tests through virtual and real simulations on the single components and the entire car are performed. From the whole set of activities those considered more relevant to the HVAC study were extracted. They are part of the three main sub-processes Target Setting, Design, Prototype&Test:

1) The Target Setting process has the purpose to identify customer needs and to convert them in technical objectives (engineered parameters) for the single systems that form the car. In practice, a number of subjective indicators, not easily measurable, are quantified and transformed into objective indicators that designers can interpret and use as a reference to derive target values.
2) Design is responsible for issuing technical documents. Technical documents include mathematical models and drawings for all car components. Mathematical models and drawings can be divided in two types: the first one relative to systems and components of the "scudato" which are not directly associated to the Style process and the second one relative to those systems and components of the car that are strongly dependent on the input coming from the Style process. The scudato contains the components belonging to the following systems: power supply, cooling, discharge, brakes, drive integration, vehicle and engine suspensions, steering, vehicle protection, interiors (seat framing), climate, and body chassis (platform and under-facia cross rail). Design activity related to these systems includes the following steps: scudato feasibility, scudato preliminary studies, scudato studies, and muletti design.

Tasks		■	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Vehicle objective definitionn	Customer objectives	1	■	●	●	●						●																														
	Technical objectives	2		■	●			●	●	●		●																														
	Vehicle architecture and decomposition	3			■			●	●	●				●	●							●	●																			
	Product Grid	4		●	●	■							●		●							●	●																			
	Shield preliminary-study	5					■									●																										
	Packaging	6						■																																		
	First cycle of virtual verification	7							■							●																										
	System performance virtual analysis	8		●						■																																
	Out-sourcing pipe development	9									■						●																									
Contractual zero-card	Sub-System Objectives	10										■	●																													
	Product card	11											■	●							●					●			●									●				
	Style boundaries/Planning	12												■		●					●																					
	BM muletti	13													■									●			●															
	Shield study	14														■								●		●																
	Piping development	15														●	■												●													
	HVAC sourcing	16																■	●									●	●													
	Condenser sourcing	17																	■									●	●													
	BM load	18																		■		●	●																●			
Two-concepts selection	N models of Style development	19																			■					●					●											
	BM model introduction and management	20																				■																	●			
	BM definition	21																					■																●			
	Muletti design	22																						■			●	●														
	Engine compartment layout development	23																							■						●											
	Second cycle of virtual verification	24																								■					●				●		●				●	●
	Muletti tooling	25																									■	●														
	Muletti development	26																										■				●										
	Pipe-compressor sourcing	27																										●	■													
One-concept selection	Two models of style development	28																												■			●									
	System prestudy/Comp.Climate for Style	29								●																●					■				●					●	●	
	Muletti verification	30																													●	■			●							
	Control drive sourcing	31																															■								●	
Style approval	One model of style improvement	32																																■	●							
	Investigations	33	●	●								●																							■							
	Parts	34	●	●								●																								■				●	●	●
	Style improvement	35																																		●	■					●
	Up-dating vehicle PDM	36																																				■				
	Performance re-validation	37																																					■			
	Prototype tooling	38																																						■	●	
	Prototype	39																																							■	
	Prototype validation	40																																		●						■

Fig. 2 The DSM of the car climate control system development process

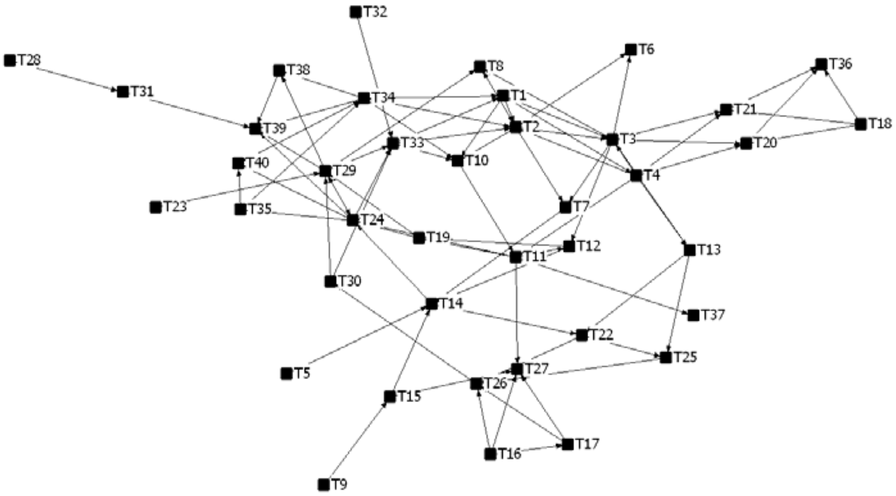

Fig 3 The Car Climate system development process network

These latter are riggings assembled in old car models to carry on experimentation and testing. Mathematical models issued from the latter activity are used to build muletti. The vehicle contains the following systems and components that are deeply influenced by the Style process: body, moving parts, external finishes, interiors, moving part finishes, sound-dampening, electrical/electronic, drive support, some parts of the climate, vehicle protection, and passengers protection systems. Design activity related to these systems include the following steps: feasibility, preliminary studies, studies, and particulars. These activity provides designers with the mathematical models used to build prototypes.

3) The Testing process includes planning design activities to perform tests, building testing artifacts, performing tests, report delivery and results diffusion. This process is thus a critical and complex process.

Two DSMs were built for each Unit of the P&PE department, respectively measuring ambiguity and uncertainty of communication flows. In total, 6 DSMs were used in the study containing values for perceived ambiguity and uncertainty of the information exchange between tasks. The specific DSMs built according to the judgment of experts within each single unit provided three different information-processing perspectives of the product development process.

In the study, the DSM data were used as the entries of the adjacency matrix. Thus, different values associated to the same relationships in each DSM reflected the information flow quality perceived by individuals working in the 3 Units, and identified 6 weighted networks, in which ties reflect the strength of the relationships and can have different values.

In order to investigate the nature of the information flow, the conventional network sociometric measurements Freeman's degree (out and indegree), and the flow betweenness centralization were calculated using the UCINET software [12]. Fig. 2 reports the basic DSM/adjacency matrix of the unweighted (binary) network (in which ties have value of 1 if two nodes are connected, and 0 if they are not connected) and Fig. 3 illustrates the network representation.

IV. RESULTS

Table 1 reports measurements for the Freeman's degree centrality and flow betweenness centrality at the network (the overall product development process) level. The degree of variability in the degrees of tasks in the observed network is expressed as a percentage (normalized) of that in a star network of the same size which is assumed as a theoretical maximum. The relative low value of the Freeman's degree centrality index in the 3 organizational units (maximum value is lower than 14%) suggests that relevant information to carry on the development process is almost uniformly distributed. Furthermore, it clearly appears that information uncertainty rather than ambiguity may be detrimental to effective communication and process tasks flow. Centralization is indeed higher for the uncertainty dimension of the information exchange. Table 1 also shows that generally at the network level outdegree is higher than indegree centralization.

TABLE I

CENTRALITY MEASURES AT NETWORK LEVEL

	Methodologies		Packaging		Climate	
	Unc.	*Amb.*	*Unc.*	*Amb.*	*Unc.*	*Amb.*
Freeman's degree						
Outdeg. centralization	12.75%	6.35%	10.15%	3.11%	13.66%	11.01%
Indeg. centralization	7.49%	5.03%	4.89%	3.76%	5.11%	5.75%
Flow betweennes						
Centralization index	18.18%	17.97%	17.96%	17.85%	18.49%	16.41%

Unc.(*Amb.*)= information flow uncertainty (ambiguity) based-network

The higher value of the outdegree centralization index is associated to a greater influence that a small number of tasks may have on the information flow directed toward other tasks.

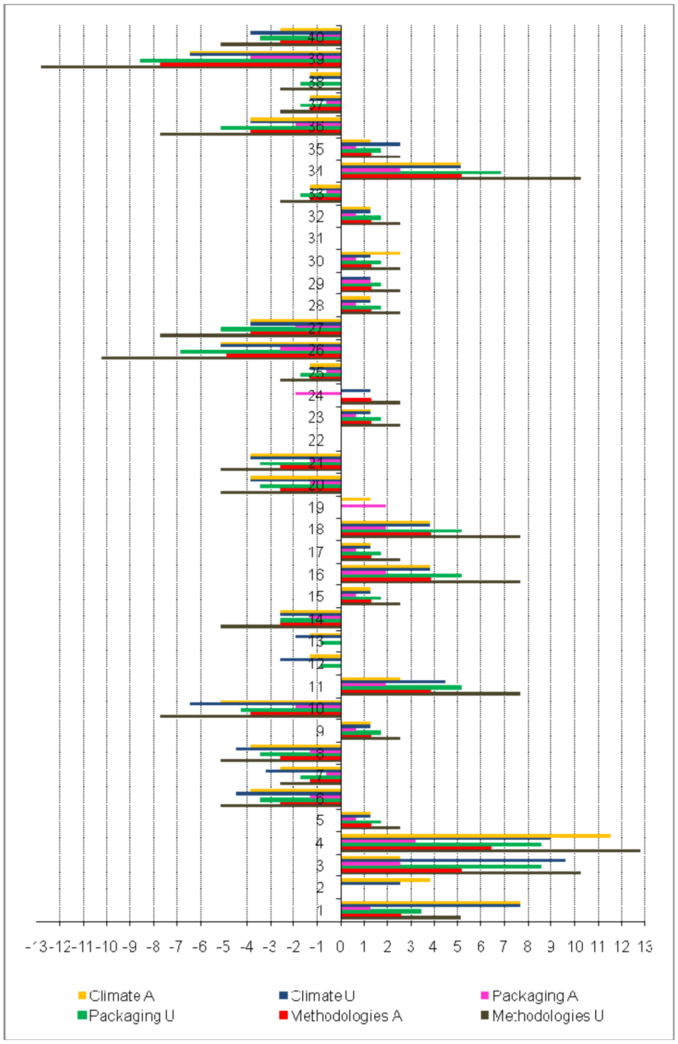

Fig. 4 Freeman's degree centrality measures, "Outdegree – Indegree" difference for all tasks

However, except for the Climate Unit, the influence of communication uncertainty is more evident than the influence of ambiguity. These "uncertainty-generating" tasks need to be taken under control. Thus a not negligible amount of low quality communication is transmitted by a reduced number of tasks. Vice versa, the lower value of the indegree centralization index shows that there is not a concentration of tasks where low quality communication is directed, and there are no prominent tasks where to focus efforts in order to improve process behavior. At the tie level, indegree might reflect how susceptible a task is to low quality communication, while outdegree might reflect how detrimental to effective communication it may be.

In the climate system development process under consideration, the betweennes centralization index values present only some negligible differences among the three organization units. Findings at the network level are also consistent with findings coming from the analysis carried on at the tie level (here not reported). Both the Freeman's centralization and betweennes indexes of only a small number of tasks showed values higher than average; henceforth differences across tasks did not identify any particularly critical situation.

While at the network level social network analysis provides insights relatively to a global behavior of the whole network, at the tie level it allows to identify critical tasks that are potential bottlenecks in information exchange during technical problem-solving associated to product development.

Fig. 4 and Fig. 5 respectively show centrality measures for specific tasks. Particularly, in Fig. 4 the "Outdegree-Indegree" difference for each task has been reported. This index was calculated twice for every organizational unit by subtracting the task indegree from the outdegree values relative to information flow uncertainty and ambiguity. It clearly emerges that:

a) both ambiguity and uncertainty decrease when the development process proceeds. Indeed, while at the beginning of the process asks "1", "3", "4" and "5" are characterized by an increase of the perceived amount of ambiguity and uncertainty (there is a generation of both ambiguity and uncertainty), at the end of the process, tasks from "36" to "40" are characterized by a decrease of the perceived uncertainty and ambiguity amount. As several empirical studies have showed, complex product development continuously moves from stages where both ambiguity and uncertainty increases to stages where the amount of these latter decreases. Technical problem-solving that characterizes product development requires new information and knowledge that – even though help engineers and technical managers to find proceeds along the stages of the process and refine concepts and technical solutions – most frequently add further uncertainty and ambiguity [8];
b) tasks may be classified into three main typologies: T1) "tasks generating uncertainty and ambiguity", T2) "tasks absorbing/annulling uncertainty and ambiguity", and T3) "tasks reducing uncertainty and ambiguity". For instance, tasks "1", "3", "4", and "5" having a positive "outdegree - indegree" difference are tasks generating uncertainty and ambiguity (T1), while tasks "20" and "21" are tasks reducing uncertainty and ambiguity as they show a negative "outdegree – indegree" difference (the amount of ambiguity and uncertainty that flow out of these tasks is lower than the amount of ambiguity and uncertainty flowing inside (T3). Finally, as an example, tasks "2", "22" and "31" are tasks absorbing/annulling ambiguity and uncertainty (T2). For these tasks, ambiguity and uncertainty inflow and outflow are well balanced.
c) uncertainty rather than ambiguity seems to have a major effect on the effectiveness of task integration and communication flow quality (the "outdegree-indegree" difference is indeed higher for perceived uncertainty);
d) generally for every task the "outdegree – indegree" difference perceived both in terms of ambiguity and uncertainty differ across the three organizational units.

Fig. 5 shows the plot of the flow betweeneess centrality measurements for all tasks. The visual analysis of the plot of

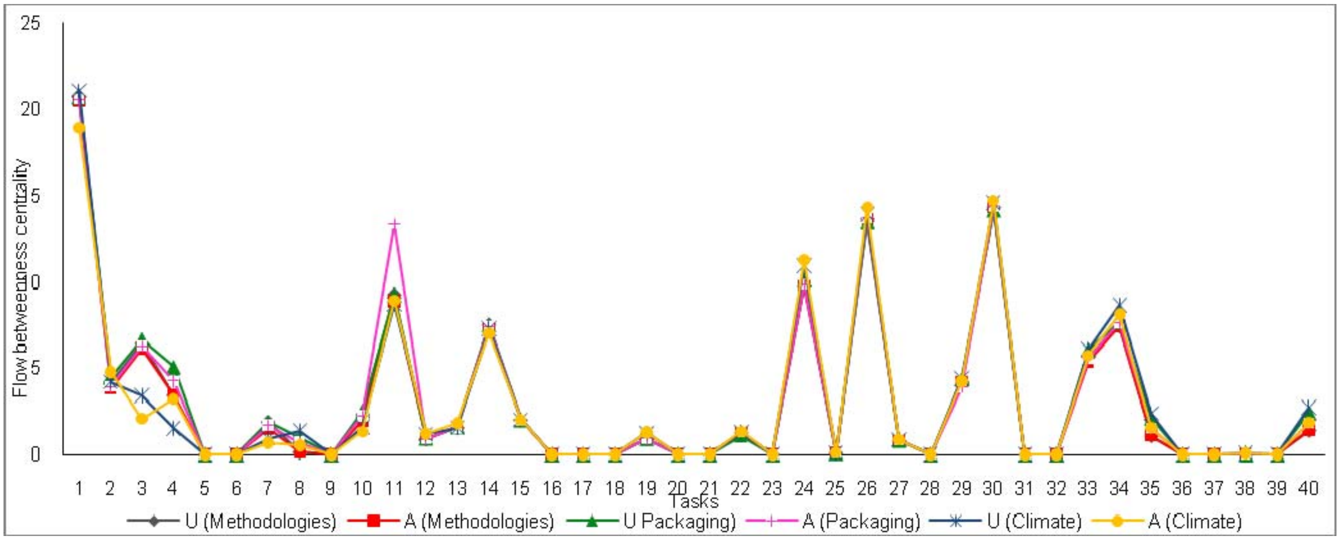

Fig. 5 Flow betweenness centrality measures

this index provides also insights to make useful considerations relative to the development process of the climate system:

e) all organizational units involved in product development – Methodologies, Packaging, and Climate – show a similar perception of critical tasks that act as intermediaries relatively to communication from a certain stage of the process (task 14). On the contrary, until this stage there is some lack of homogeneity in the judgments given by people during field analysis interviews relatively to the information quality. That is probably due to the fact that there is a complete sharing of how the product development process proceeds and of the critical tasks of it only after task 14;

f) as it already appeared from the analysis of data illustrated in Fig. 4, the process evolves showing a great number of critical tasks as to the exchange of useful information.

V. CONCLUSION

Even though the analysis presented here has only used two centrality measures, the study showed how DSM and SNA can be fruitfully used together as a tool to investigate and improve the product development behavior. Formal SNA provides formal descriptors (definitions and measures) to characterize groups of tasks and teams, to characterize the process/network properties, and – when large process/networks are investigated - it allows us to test statistical models about relationships and structure.

A major limitation of SNA is due to the static perspective adopted in modeling processes. A network represents a structure at one point in time and dynamic inferences should be made over longer periods of time. The assumption made in SNA is that relationships are relatively stable over time. Thus, to investigate complex network dynamics one needs look at how a networked process change over time. That implies great effort and resource consumption to collect data at different times. The product development process could also benefit from the adoption of a greater number of SNA measurements. Indeed, real system architectures might not be easily described by a single typology of structural metrics.

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