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Abstract

Using the formalism provided by the Systems Thinking approach, the dynamics present when operating multidisciplinary teams are examined in the context of the NASA Langley Research and Technology Group, an R&D organization organized along functional lines. The paper focuses on external dynamics and examines how an organization creates and nurtures the teams and how it disseminates and retains the lessons and expertise created by the multidisciplinary activities. Key variables are selected and the causal relationships between the variables are identified. Five 'stories' are told, each of which touches on a different aspect of the dynamics. The Systems Thinking Approach provides recommendations as to interventions that will facilitate the introduction of multidisciplinary teams and that therefore will increase the likelihood of performing successful multidisciplinary developments. These interventions can be carried out either by individual researchers, line management or program management.

1. Introduction

Successful multidisciplinary work, whether in engineering or any other field of endeavor, is dependent on the organization that carries it out. Not only does multidisciplinary work require good methods and efficient tools, it requires methods and tools that are matched to the responsible organization.

Indeed, one could conceive of devising multidisciplinary optimization processes that concentrate design decision-making in a single, large optimization problem. Instead, significant efforts are expended in devising processes that recognize the mostly distributed nature of the decision-making process carried out in typical design organizations. The emphasis is on the coordination of the distributed decision-making processes that take place in mostly single-discipline teams (see Kroo,[1] for example). Clearly, there are other reasons for which one would want a decomposed multidisciplinary optimization process, including computational feasibility and availability of disciplinary tools for simulation and optimization. However, a major factor for such emphasis remains that the proposed methods can be implemented in current organizations without requiring radical changes in the roles of the various participants.

If one accepts the premise that multidisciplinary methods and the supporting teams ought to be matched, then it is necessary to observe how multidisciplinary teams are created and how they operate. In particular, one must be able to determine what makes an organization conducive to creating and operating successful multidisciplinary teams. To do so, one should observe both internal and external team dynamics. Internal dynamics have to do with what makes a particular team successful in terms of its own operating rules and how the team members interact with each other. External dynamics have to do with how an organization creates and nurtures the teams.

The purpose of this paper is to relate an effort at the NASA Langley Research Center (LaRC) to observe multidisciplinary team dynamics using a Systems Thinking approach. In this context, a multidisciplinary team is defined as a team that combines different engineering disciplines or significantly different aspects of the same discipline. At LaRC, such a team almost always crosses organizational boundaries, requiring participation from members of different organizational elements.

Based on interviews with members of three multidisciplinary teams that were ongoing or had recently completed their assignments, the authors 1) identified the main variables affecting team dynamics, 2) traced the causal relationships linking those variables, 3) built a model of the dynamics of the

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multidisciplinary teams, and 4) identified candidate interventions to improve those dynamics in specific circumstances. This paper will focus on external team dynamics. A companion paper by Waszak et al.[2] discusses internal team dynamics.

There are several sources that point out the influence of external (organizational) factors on team performance; team models that focus solely on internal team dynamics are inadequate (Gresick[3], Morgan et al.[4]). Organizational goals and expectations, as well as organizational support can influence team performance. Teams do not operate within a closed system but are influenced by outside factors. Specific mention has been made of the importance of organizational influence across subunits and of the environment the organization creates for teams (Jackson et al.[5]). Tichy and Sherman[6] show that organizations are encouraged to emphasize cooperation and weak interunit boundaries as a way of strengthening team performance.

Multidisciplinary teams are cross-functional. As such, they were introduced as management tools over 30 years ago, along with the matrix concept of organization. The interested reader should refer to the relatively recent paper of Ford and Randolph[7] for a review of existing literature on the subject. A few points relevant to this study will be made here.

Larson and Gobeli[8] and, more recently, El-Najdawi and Liberatore[9] have examined the advantages and disadvantages of a matrix structure of management. Among the advantages, they cite efficient use of resources, better project integration, improved information flow, flexibility, discipline retention (Disciplinary experts are matrixed for the projects. Upon project completion, they return to their home organization, thereby maintaining an available pool of specialists. Between projects, they may be strengthening their expertise and improving their tools), improved motivation and commitment. Among the disadvantages of the matrix structure, they examine power struggles, heightened conflict, slow reaction time, monitoring and controlling difficulty, excessive overhead, increased stress.

A number of studies have attempted to correlate project performance with organizational structure. Katz and Allen[10] determine that best performance occurs when the line manager focuses on the quality of the tools, model, tests or processes going into the project, while the project manager focuses on gaining the backing of higher levels of management, obtaining critical resources, and coordinating the effort among the different line organizations. They insist, however, that line managers and project managers should have a balanced influence on project team member salaries and promotions. In their detailed studies, Larson and Gobeli[8,11] correlate project performance to the organizational structure, with the scale for the latter placed on a continuum ranging from the pure functional organization to the pure project organization. They observe that project effectiveness, as measured by cost control, schedule and technical performance, is best in an organization they define as the *project matrix*, where, "A [project] manager is assigned to oversee the project and is responsible for the completion of the project. Functional managers' involvement is limited to assigning personnel as needed and providing advisory expertise."

In general, publications on matrix organization and project management form a good backdrop against which to observe and study multidisciplinary team external dynamics. Perhaps Davis and Lawrence[12] (as quoted in Ford and Randolph[7]) offer a hint of the challenges to be faced in introducing such teams into a functional organization when they write, "…a successful matrix must be grown instead of installed…"

This paper begins with a brief primer on the Systems Thinking approach and describes the R&D organization considered for the study, stating the assumptions made in the course of the modeling effort. The dynamics observed are described in five 'stories' highlighting different salient components of the model and pointing at possible interventions to alter the balance between disciplinary and multidisciplinary work in the organization. After a commentary on the complete model, the paper concludes with remarks on the lessons learned from the model and on the usage of the System Thinking formalism as a tool for charting the organizational dynamics at work.

2. Systems Thinking—a Brief Primer

Systems Thinking follows an approach that recognizes the interconnectedness of the subsystems making up a system. Senge[13] defines it as the fifth discipline of learning organizations, "…a conceptual framework, a body of knowledge and tools ... to make the full patterns clearer, and to help us see how to change them effectively". Systems Thinking aims at discovering the structure behind the observed systems dynamics, so that it can be understood and affected, if desired.

The Systems Thinking approach applies to any kind of system, whether physical or organizational. In a sense, the literature on Multidisciplinary Analysis and Optimization, as well as similar literature in the fields of systems analysis and design reports on diverse Systems Thinking models and tools devised to analyze and engineer coupled physical systems.

Senge et al.[14] have described a method to model complex systems using a Systems Thinking approach. It begins by identifying the *variables* that affect the system and, if possible, by tracing their variation over time. These variables have to be observable; they should also be measurable, if only in a very approximate manner, identifying at least whether the variables increase or decrease with time or with other selected inputs.

Causal relationships are identified that determine how one variable influences other variable(s). These relationships can be diagrammed by links and result in loops that can be either reinforcing or balancing, depending on whether a perturbation of a variable sets off an unstable response (*reinforcing loop*) or a stable response (*balancing loop*). Various combinations of reinforcing loops and balancing loops can be created to model archetype behaviors (*archetypes*); these combinations seem to occur repeatedly in various studies of different types of systems. They have typical dynamics, and *interventions* can be devised to alter the dynamics and reach a desired trend in the variables. Occasionally, *external factors* are identified that have a significant impact on the dynamics, yet are not directly affected by it. In addition, it is useful to identify *mental models* held by the protagonists in the dynamics observed, as they can serve to explain some of the key causal relationships.

For a realistic system, the resulting combination of reinforcing loops and balancing loops is more complicated than the basic archetypes. However, some of these basic archetypes can usually be identified in the complete picture, helping to explain elements of the overall dynamics.

3. The Case Study, Relevant Assumptions

The LaRC organization responsible for implementing research and development (in all technical areas, except Atmospheric Sciences) is the Research and Technology Group (RTG). Comprised of approximately 700 civil servants, the RTG is organized in six functional divisions, each responsible for research in a key technical area. These areas are: 1) Aero- and Gas-Dynamics, 2) Flight Dynamics and Controls, 3) Fluid Mechanics and Acoustics, 4) Flight Electronics Technology, 5) Materials, and 6) Structures. The divisions are further divided into branches, each responsible for relevant sub-areas. By and large, divisions and branches focus on disciplinary developments, although some of them perform multidisciplinary work. The functional organizations are the keepers of the core competencies, internally defined as "…the distinguishing integration of skills, facilities, and technological capabilities that provide Langley with the unique capacity to perform its mission. These core competencies differentiate Langley from other organizations, …"

In contrast, the LaRC organizations responsible for research program content are small program offices (POs), located outside of the RTG. Whether overseeing base or focused programs, the POs' responsibility is to 1) interact with the external customers, 2) define the technical program content, 3) allocate funding, 4) monitor the research, and 5) coordinate the work with other organizations engaged in similar activities. A program manager engages in program planning (and replanning) to define and update the research portfolio for his/her program. This planning exercise is typically conducted over a short period of time by a team made up of the program manager and researchers from the RTG, engaged in that particular research area. Work packages are proposed and some portfolio analysis is performed to select the collection of work packages that best meets the objectives of the program. So, while the POs decide on the balance of the research portfolio, representatives of the RTG are directly involved in the decision process.

This is a loose matrix arrangement in that, while the POs are responsible for the content of the research program, the RTG is completely responsible for its implementation. Technically, a PO has little authority on the details of the program implementation, nor on who is assigned to perform the work. Should a work package be selected that is disciplinary, then the functional structure exists to perform the work naturally. If, instead a work package is selected that is clearly multidisciplinary, then a multidisciplinary team must be assembled. While he/she may facilitate the organization of the team, the program manager has limited influence on the composition of the team and its operation.

In many respects, this structure conforms to the *functional matrix* structure which Larson and Gobeli[11] characterize by "A person is formally designated to oversee the project across different functional areas. This person has limited authority over functional people involved and serves primarily to plan and coordinate the project. The functional managers retain primary responsibility for their specific segments of the project."

This paper assumes that one can decide to carry on disciplinary (SD, as in single-disciplinary) work or multidisciplinary (MD) work. The program planning exercise is viewed as the process in which the balance is set between disciplinary work and multidisciplinary work. It is further assumed, for the sake of the

discussion, that program planning is conducted in a fixed resource environment, so that an increase in multidisciplinary work inevitably results in a decrease in disciplinary work, and vice versa.

Note that multidisciplinary teams are made up mostly of disciplinary specialists who contribute their expertise to the task at hand. In addition to disciplinary experts, however, multidisciplinary teams will also include researchers whose background is specifically multidisciplinary, whether as system study practitioners or as multidisciplinary methods or applications experts.

4. Contributing Stories

This section describes the System Thinking model through five different stories. Each story corresponds to a different set of loops of the model and describes a different aspect of the dynamics at work. Each story follows a variation on an archetype of the System Thinking discipline; when relevant, the discussion will identify that archetype. Additional details are available on the project website <http://dcb.larc.nasa.gov/larcst/CaseStudies/CaseStudy2.html>.

4.1 Key Variable, Explicit/Implicit Pressure Concept

In a fixed resource environment, the key variable in the dynamics is the ratio between MD activities and SD activities (*MD/SD activity ratio*). It is assumed that, MD or SD activities correlate directly to the resources invested. The activities can include computational simulation, experimental development, whether in the lab or in flight, projects funded through university grants and industry contracts, or any combination thereof. The resources cover the full cost of carrying out activities, including workforce, acquisition, fabrication, experimental and computational facility maintenance, upgrade and construction.

Historically, NASA LaRC has had a very strong tradition of SD work. However, new aeronautical concepts are envisioned for revolutionary technology leaps. These concepts are highly coupled, and a limited experimental or numerical database exists to support simulation and design; the need for multidisciplinary developments therefore increases.

The objective in this study is to identify the forces at work in attempting to increase the number of multidisciplinary activities or, to increase the MD/SD ratio. Given the fixed resource assumption made earlier, this automatically implies decreasing the number of disciplinary activities.

During the research portfolio selection, two pressures are acting in favor of increasing the MD/SD activity ratio. The *explicit pressure* has to do with quantifiable elements such as the cost of a proposed research work package, the benefits expected from carrying out the work, the commitment the organization has for this type of work. One would expect that this pressure is exerted directly during the research portfolio selection process, particularly when the work packages submitted are ranked based on quantitative metrics.

In contrast, the *implicit pressure* has to do with qualitative elements, like the affinity or familiarity individual organizational elements or researchers have with a particular technical area. One would expect this pressure to act in a more subtle way as POs, individual organizational elements, and researchers contribute to the selection process.

4.2 Organizational Commitment

The first story ties the number of activities in a particular area (*MD or SD activity*), the benefits accrued from those activities, and the organizational commitment to those activities. It is diagrammed in Fig. 1.

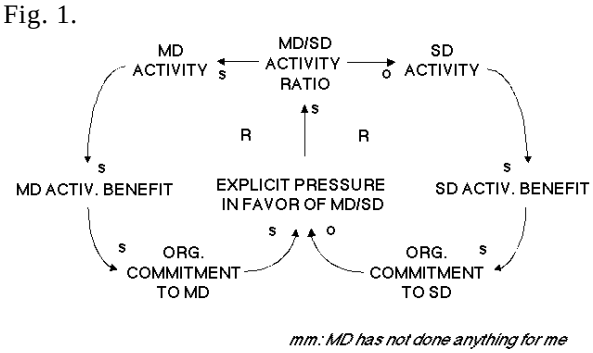

Fig. 1 Organizational commitment impact

MD(SD)[#] *benefit* results from carrying out an MD(SD) activity; it includes technical results as well as positive internal or external customer feedback. *Organizational commitment to MD(SD)* is the disposition that the organization has for performing MD(SD) developments. The diagram shows the variables in the story linked by arrows indicating causal relationships between the variables. An ‘s’ near an arrowhead indicates that as the influencing variable increases, the influenced variable moves in the same direction; an ‘o’ indicates that as the influencing variable increases, the influenced variable moves in the opposite direction. An ‘R’ indicates a reinforcing loop, in later figures, a ‘B’ will denote a balancing loop.

Looking at the left-hand side of Fig. 1, the story says that increasing the MD/SD activity ratio will result in accruing additional MD benefits, which in turn will increase the organizational commitment to MD, and as a consequence, will increase the explicit pressure to increase the MD/SD activity ratio further. This is a

[#] For brevity, MD(SD) is used to denote MD (or SD).

reinforcing loop, so any perturbation of the key variable is amplified. However, looking at the right-hand side of Fig. 1, the story says that increasing the MD/SD activity ratio will decrease the number of SD activities, decrease the resulting SD benefits, and decrease organizational commitment to SD, further increasing the explicit pressure to increase the MD/SD activity ratio. This is also a reinforcing loop.

This story predicts a situation where, if no other dynamics are involved in the model, the key variable (MD/SD activity ratio) increases without bound, resulting in increasing numbers of MD activities, and decreasing numbers of SD activities, to the point where only MD activities are carried on. Had one argued in favor of decreasing the MD/SD activity ratio, the reverse situation would have occurred, where the SD activities increase while the MD activities decrease. As will be seen in the next subsections, additional dynamics are at work in this organization that thwart this potential unchecked growth. Nevertheless, LaRC has a strong tradition of SD work. As a result, the existing balance is clearly in favor of SD work, so that if no other action were taken, the model in this first story would predict the disappearance of MD work.

In the System Thinking formalism, this is categorized a "success to the successful" archetype (Senge[13]). It is typical of situations where two (or more) activities share the same resource. If external factors exist that provoke an imbalance between the two competing activities, then the tendency is for that imbalance to amplify.

Team interviews indicate that one mental model plays an important role in the story. It asserts that "MD work has not done anything for me." It is the perception by organizations that little or no benefit has ever accrued from being involved in MD activities. This model could result from two different influences. First, the relatively low historical MD/SD activity ratio implies that few MD benefits have accrued over the years that could sway organizational commitment in support of MD. Second, it may be that, even as MD activities were carried out, the benefits (or lack of benefits) of using an MD solution to a problem as opposed to an SD solution were not evaluated, documented and subsequently advertised.

An external factor influencing this dynamic is the total amount of resources available for R&D activities. Our assumption that the total amount of resources is fixed is quite constraining. It implies that increasing MD/SD will reduce the number of SD activities. It would clearly be an easier management situation if one could increase MD activities without affecting SD activities. Note that, although the point will not be repeated in the next stories, this external factor is of major influence throughout the discussion.

The Systems Thinking interventions recommended by Senge et al.[14] for a situation described by a "success to the successful" archetype are to 1) base resource allocation on potential and demonstrated success, 2) look for overarching goals for the competing activities, 3) break the resource link, and 4) look for additional resources, if possible. Because of the initial assumption, intervention 4 is not applicable. For this situation, the following interventions are suggested.

1. Drive the portfolio selection process with cross-functional goals (intervention 2, above). During the portfolio selection process, high marks will be given to work packages that align with the program goals. Each program can be given strong multidisciplinary objectives, thereby favoring multidisciplinary developments. By and large, this is the objective of the current functional organizations/program offices matrix LaRC is using (Sec. 3).

2. Set the MD/SD balance artificially (intervention 3). This could come in the form of planning guidelines on the MD/SD activity ratio. The idea here is to temporarily suspend the link between organizational commitment and MD/SD balance, by setting aside some time to perform more MD activities thereby accruing more benefits and the resulting organizational commitment for MD.

3. Use reliable system metrics to set the MD/SD balance (intervention 1). While both MD and SD work packages are likely to support the program goals, comparison of the relative merits can be difficult. System metrics are needed that enable a comparison on equal footings.

4. Determine, document, and advertise MD benefits (intervention 1). The objective is particularly to document the benefit of an MD approach to a problem versus an SD approach. Depending on the circumstances, the same problem may require an SD or an MD approach. The existence of system metrics and the documentation of benefits will help in deciding whether to take the SD route or the MD route.

4.3 Technical Maturation

This second story (Fig. 2) introduces the new variables of *technical maturation*, a measure of how mature a particular technical area is, and *cost/benefit* , the cost-per-unit technical benefit of an activity. Note that the loops include those discussed in the previous subsection.

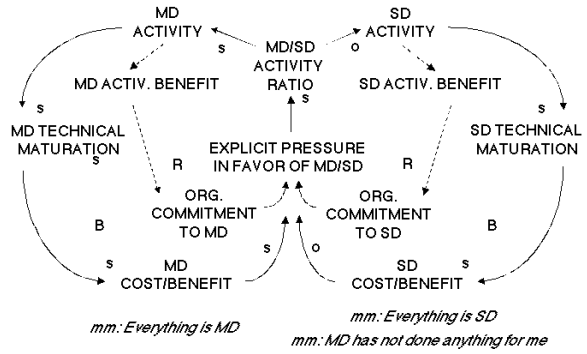

Fig. 2 Technical maturation impact

Early in the life of a technical area, whether disciplinary or multidisciplinary, technical maturation is very low; progress comes quickly, and for a relatively limited amount of resources. In consequence, the cost/benefit of technical developments is low. As more technical developments are contributed, technical maturation increases. At the same time, as explained in the previous subsection, benefits accrue from development successes, strengthening the commitment to work in that technical area.

Later, the "low-hanging fruits" have been picked and the cost/benefit curve steepens, as more resources are needed for a given amount of development. Eventually, maturity is reached, the law of diminishing returns sets in, and additional, meaningful developments are very expensive, possibly prohibitively so. This renders the cost/benefit unattractive, causing explicit pressure to reduce the number of activities in that technical area.

While the concept of technical maturity is understandable, it is unclear how to measure directly the state of maturation of a technical area, let alone the relative states of maturation of different technical areas, whether disciplinary or multidisciplinary. Perhaps one needs to infer technical maturity from some cost/benefit metric. It is clear, however, that the state of maturation in multidisciplinary developments currently is lagging behind that of most disciplinary developments.

While early on technical benefits were easier to reap from SD activities, at some point, problems need to be treated in a multidisciplinary fashion to get the best return on resources. It is quite conceivable however, that as multidisciplinary methods mature, the maturation levels may cross again, indicating that the next advantageous development, from a cost/benefit standpoint, again becomes disciplinary.

Three mental models are at work in this story. The first is the notion that "every problem is SD" or that one can get to the required solution without consideration for the effect of other disciplines. While at the discipline level this appears to be the minimum-cost approach, it is unclear that the resulting benefit and cost/benefit will make that a desirable solution. The second model, is the contradictory notion that "every problem is MD", the belief that, in any engineering problem, all the disciplines are coupled in some fashion and that all disciplines must be introduced for a correct solution. This pushes in favor of an MD treatment, while a cost/benefit analysis supported by system studies would determine whether the extra cost is indeed warranted by the benefits accrued. Clearly, different people hold the two mental models above. The third mental model, is, as in the previous subsection, the perception that "MD has done nothing for me," that the benefits of engaging in an MD activity are not obvious to the participants.

The loop structure of Fig. 2 combines the "success to the successful" loop from the preceding subsection with two additional balancing loops. The interventions derived from this second story are closely related to the last two from the previous subsection, except that instead of suggesting simply the use of system metrics, possibly related to the system performance, cost, or any other overall metric, this story suggests to combine the system metrics with development cost, thus evolving cost/benefit metrics. The following interventions are suggested.

1. Develop effective development cost/benefit metrics to compare the values of the technical developments suggested for MD and SD. The R&D portfolio balancing then focuses on overall goals or outcome and on the system being contributed to, rather than on functional goals and outcome.

2. Make it a requirement for proposals for MD development to predict and subsequently demonstrate the cost/benefit of the proposed MD treatment of the problem as opposed to an SD treatment of the problem.

4.4 Individual Proficiency, Organizational Competency

The third story (Fig. 3) introduces the new variables of *MD(SD) proficiency*, (the individual understanding of and experience with the MD(SD) technical area of interest), *SD Competency*, (the organization's alignment with its core competency definition), and *MD(SD) cost/activity* (the cost per MD(SD) activity).

This story tells how, as additional MD(SD) work is carried out, individual contributors gain more understanding and experience with the MD(SD) field of interest. As a result of the increased proficiency, MD(SD) activities can be performed at less cost/activity. Also, additional benefits accrue, resulting in improved cost/benefit. Both put additional external pressure in favor of MD(SD) activities.

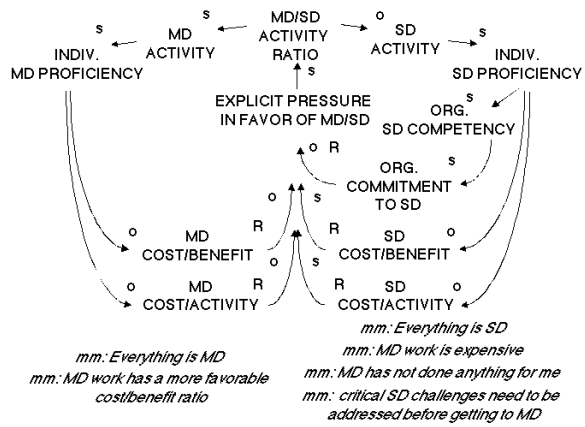

Fig. 3 Individual proficiency and organizational competency impact.

The increased individual proficiency has an additional impact in favor of SD activities. The better individual SD contributors become at their work, the more they contribute to the alignment of their organizational element with the core competency it is tasked with maintaining (see Sec. 3). Given that no organizational element is tasked with maintaining an MD core competency, there is no corresponding reinforcement on the MD side.

The resulting set of loops follows the 'success to the successful' archetype introduced in Subsec. 4.2, except for the additional reinforcing loop corresponding to organizational competency. The historically low MD/SD activity ratio and this additional loop contribute to reacting an increased MD/SD activity ratio.

Several mental models play an important role here and include "everything is SD," "everything is MD," "MD has not done anything for me," as discussed before. Three additional mental models appear. The first is the position that "critical SD challenges need to be addressed before getting to MD." The second states that "MD work is expensive,"; it is the realization that if one needs to implement a multidisciplinary solution to a problem, several engineering models need to be developed, interfaces need to be provided, and generally, the cost/activity increases. On the other hand, another, somewhat contradictory mental model asserts that "MD work has a more favorable cost/benefit ratio"; it is the belief that, somehow, the benefits resulting from combining disciplines far outweigh the additional cost. Clearly the latter two mental models would not be factors if system cost/benefit metrics were available, as argued in the previous subsections.

All the interventions introduced in Subsecs. 4.2 and 4.3 are applicable here. Three additional interventions that will facilitate increasing the MD/SD activity ratio can be derived from this story:

1. Improve MD individual proficiency by providing MD education to existing researchers and, when possible, by hiring new employees with MD education and/or experience.

2. Compensate for the lack of an organization MD competency reinforcing loop by tasking an organizational element at LaRC with nurturing an MD core competency. It is probably not desirable to create another functional organization responsible for MD work across the center. Rather, making the POs the keepers of the MD competency in some implementation of the matrix organization concept might be the right approach. In addition, a line organization must be maintained that pursues fundamental research on MD methods.

3. Make an integration competency an integral part of the core competencies ascribed to the functional organizations. In other words, require all the functional organizations not only to cultivate and grow their own disciplines, but to make them multidisciplinary-capable by using engineering models common with other disciplines, developing compatible interfaces and providing sensitivity information for integrated analysis and design.

4.5 Individual Affinity and Familiarity

The fourth story (Fig. 4) focuses on the variables that affect the implicit pressure in favor of a high MD/SD ratio, these are the *MD(SD) familiarity* and the *MD(SD) affinity*. Here, familiarity is defined as the individual knowledge of the tools, methods, benchmarks of the technical area of interest, while affinity is the individual propensity to engage in activities in the technical area.

The story here is that as additional MD(SD) activities are conducted, individual participants gain familiarity and affinity for the particular MD(SD) technical area. Affinity and individual proficiency (Subsec. 4.4) reinforce each other as well. In consequence, when it is time to propose new work packages for program planning/replanning, individual researchers are more likely to propose work in the technical area with which they are familiar and for which they have increased affinity.

Here again, the relevant Systems Thinking archetype is of the "success to the successful" type. Historically high familiarity and affinity for SD work results in implicit pressure opposing an increase in MD/SD activity ratio.

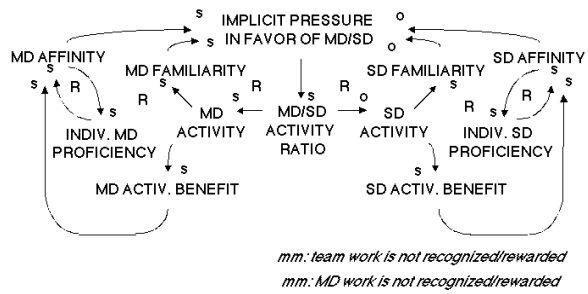

Fig. 4 Individual familiarity and affinity impact.

Because MD activities are conducted in teams, MD affinity strongly depends on willingness to participate in cross-functional team activities. This is a significant external factor for this loop and it is examined in the paper on internal team dynamics by Waszak et al.[2]

Two mental models are hampering attempts at increasing the MD/SD ratio. The first is the perception that "teamwork is not recognized/rewarded." Given the organization described in Sec. 3, no organization is explicitly responsible for assembling, growing, and maintaining the teams required for MD developments. In consequence, recognition and reward may or may not be given, depending on whether or not a functional organization feels ownership of the team. In addition comes the realization that "MD work is not recognized/rewarded". As argued by Waszak et al.[2], while closely related to the first mental model, this mindset also recognizes that SD experts working in MD applications tend to work below their own discipline's state of the art (see Subsec. 4.6). This reduces the recognition SD experts gain from their peers and managers, thereby lessening their affinity for MD activities.

Three interventions derived from this fourth story address the mental models strengthening MD affinity.

1. Recognize and reward teamwork.

2. Provide the organizational structure needed for creating and maintaining effective teams.

3. Encourage MD work by recognizing that while SD participation in MD work may be below the SD state of the art, the innovative contribution is in the interfacing of the various SD models or methods and the solution that explicitly looks for the joint impact of the disciplines involved.

4.6 Technical Maturation Gap

The final story (Fig. 5) introduces two additional variables. The *SD/MD technical gap* is the gap between the degree of sophistication of the state of the art in SD technologies and the state of the art in MD technologies. The *SD sophistication in MD activity* measures the complexity of the SD models and tools that can be handled by the current MD models and tools. It is closely related to the technical gap and decreases when the gap increases.

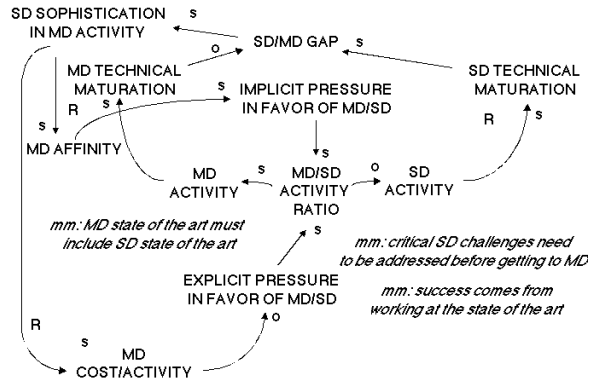

Fig. 5 Technology maturation gap impact.

The story posits that because of the historically low MD/SD ratio, technical maturation has increased faster in SD than in MD. As a result, state-of-the-art MD tools are increasingly less adequate to incorporate state-of-the-art SD tools when conducting MD applications. This process is self-sustaining. As discussed in Sec. 3, MD applications are carried out by cross-functional teams that include disciplinary experts. A consequence of this gap is that these experts are unable to work at the state of the art in their own discipline. As a result, their affinity for MD work decreases; this results in some implicit pressure in favor of maintaining or increasing the level of SD activities over MD activities, keeping the MD/SD activity ratio low.

However, those MD applications that are implemented with high-maturity SD components will prove to be quite expensive. Indeed, allowances need to be made in the implementation for more complex models and tools than the existing MD methods were designed to incorporate; alternately, new generic MD developments or accommodations must be made. The high cost of the MD applications will increase the implicit pressure in favor of SD work.

The resulting loops are all reinforcing and follow again a "success to the successful" archetype. An additional reinforcing loop arises from the fact that the maturation gap adds to the cost of MD activities; there is no such effect for SD activities.

Three mental models are contributing to this story. The first is the position introduced in Subsec. 4.4 that "critical SD challenges need to be addressed before getting to MD". The second is the belief that "success comes from working at the state of the art"—that one does not get reward or recognition from working below the SD state of the art. This applies to SD researchers

who risk to loose standing with their peers or MD practitioners whose MD models, theories, and methods seem irrelevant when confronted with comparable SD models. This is closely related to the "MD work is not recognized/rewarded" mental model introduced in Subsec. 4.5. Finally, the third mental model is "MD state of the art must include SD state of the art". The perception, that, to get a meaningful MD results, one must use the most refined SD tools.

The interventions suggested for this final story include those defined in Subsec. 4.2 and 4.3 addressing the "success to the successful" archetype. Additional interventions here address the balance of SD sophistication in MD activity requiring work on both SD and MD.

1. Carry out generic MD developments to support more sophisticated SD tools and methods, and to integrate more of the relevant disciplines.

2. Make key SD methodologies MD-capable by providing 1) interfaces to other SD methodologies, 2) ties to commonly accepted modeling descriptions, and 3) sensitivity information that enables trading among participating disciplines in an MD environment.

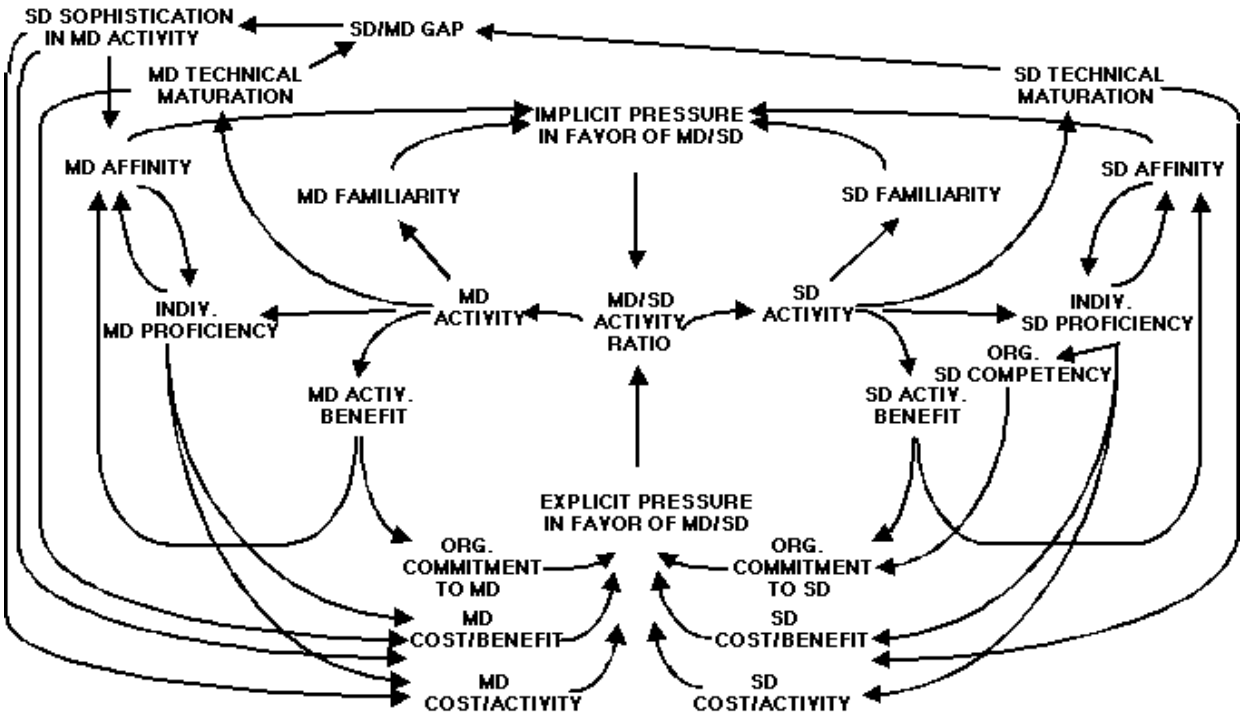

Fig. 6 Multidisciplinary team external dynamics, System Thinking model.

5. The Whole Story

Fig. 6 combines the five stories discussed in the previous section. For the sake of clarity, the notation relating to the influence of causal links (o/s, Fig. 1) and the effect of loops (R/B, Fig. 1) has been dropped. Full details are available on the project website <http://dcb.larc.nasa.gov/larcst/CaseStudies/CaseStudy2.html>. The lower part of the model contains the variables affecting the explicit pressures in effect during the portfolio selection process; the upper part of the diagram relates to the implicit pressures. The model is roughly symmetric with respect to the vertical axis. Variables and loops on the right-hand side pertain to disciplinary work, variables and loops on the left-hand side pertain to multidisciplinary work. The symmetry reflects the assumption that resources can be invested either into disciplinary work or into multidisciplinary work, and that, in general, the same variables and causal links can be defined for both types of developments.

The dominant archetype of the model is of "the success to the successful" type. In that sense it presents the choice between disciplinary and multidisciplinary work as a win-lose proposition. However, central to the interventions and prominent in the feedbacks acting on explicit pressures is the recommendation to weigh contributions to the portfolio on the basis of system cost/benefit metrics and development-cost-to-system-benefit metrics. This ensures that the work eventually

performed, whether disciplinary or multidisciplinary, is that which benefits the programs cross-cutting objectives.

"Success to the successful" archetypes are comprised of a combination of reinforcing loops. This suggests that one only needs to jump-start the loops in a direction favorable to MD for MD benefits to accrue and for the dynamics to result in increased pressure in favor of more MD work. However, note that nowhere in this discussion has the concept of time delays been brought up; yet they are critical factors in the dynamics of systems. It is clear that time is a factor in this model and that, for example, there will be a delay before an initial MD/SD activity ratio increase is felt throughout the system and before it influences favorably implicit and explicit pressures.

Only two asymmetries are apparent in the diagram. The first reflects the fact that no organizational entity is invested with an MD core competency. The second highlights the technical maturation gap between disciplinary tools and methods and multidisciplinary tools and methods.

6. Concluding Remarks

6.1 Lessons Derived from the Model

The interventions discussed in Sec. 4. provide possible approaches to increasing the proportion of multidisciplinary developments performed by the organization described in Sec. 3. These interventions can be carried out at different levels.

At the individual researcher level, there is a need for developing effective system benefit metrics and development-cost-to-system-benefit metrics. In addition, as multidisciplinary developments are proposed and carried out, their expected benefit over disciplinary solutions must be evaluated *a priori* and their actual benefit verified *a posteriori*. Disciplinary developments need to be implemented that permit incorporation of key disciplinary technologies in complex multidisciplinary applications. Also, generic multidisciplinary developments need be carried out to incorporate the most detailed disciplinary methods and models available.

Line organizations are the keepers of core competencies and as such have the power to endow a particular organization or organizational element with a multidisciplinary core competency. A line organization needs to be maintained to support MD work by developing generic MD methods and tools, thereby participating in the strengthening of an MD core competency. In addition, individual disciplinary organizational elements must add an integration element to the definition of the core competency that they are supporting. To maintain this integration element, line organizations need to hire, educate, and groom a workforce that has a diversified background and that is knowledgeable of generic multidisciplinary methodologies. Finally, the line organizations must provide the organizational elements needed to create and maintain effective teams.

Program offices define the research portfolio and in so doing can drive its definition by using cross-cutting goals. Because their oversight cross organizational boundaries, they play a unique role in the keeping of an MD core competency. To assess the suitability of proposed contributions to the portfolio, they need to use reliable system benefit metrics and development-cost-to-system-benefit metrics. They must also make it a requirement for proposed MD contributions that their expected benefit over SD solutions be evaluated *a priori* and verified *a posteriori*. They may need to artificially raise MD/SD activity ratio temporarily to gain time for multidisciplinary benefits to accrue.

6.2 Observations on the Modeling Approach.

Applying the Systems Thinking formalism described in this paper has produced a model of the multidisciplinary teaming dynamics, as extracted from the interviews carried out on the selected teams, in the LaRC Research and Technology Group. This model is strictly valid for the organization observed, although it is likely to feature many of the components present in other R&D organizations' dynamics.

Although the System Thinking model proposed for this R&D organization is very qualitative in nature, it is quite similar in principle to an engineering model for a design concept. The engineering model is validated by how well it predicts the behavior of the concept in a selected set of test situations. Once validated, it can be used to extrapolate the behavior of the concept when it is altered or the testing conditions are changed. Likewise the usefulness of the organizational model described here can only be tested by how well it predicts the response of the system to changes within the system (organization) or to external conditions (environment).

At first look, the type of model that evolved from this study is quite intuitive. One might be tempted to dismiss the use of the Systems Thinking formalism as an unnecessary complication. However, this exercise has revealed the necessity to provide some discipline to the process. Systematic identification of the variables at work and their interactions reduces the risk of omitting a critical influence. In addition, as demonstrated here, identifying standard archetypes in a model systematically points at possible interventions.

Understanding the dynamics of a system is a required first step before modifying the system to correct an unwanted behavior or to obtain a different response. Therefore, using the Systems Thinking formalism is a logical first step before adjusting or redesigning an organization, or before addressing an organizational issue.

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