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Uchchatar Avishkar Yojana

Title of Proposal	Multi-Disciplinary Optimization in Additive Manufacturing
Proposal ID	
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Ministry/Dept. of relevance	Ministry of Heavy Industries and Public

Executive summary (not exceeding 500 words)

Additive Manufacturing is the new way of manufacturing that can change the way industry creates industrial grade components. This new method has shown potential of reducing the weight of components leading to improved fuel efficiency in power generation products.
New and radical designs that could not be manufactured by conventional methods can be brought to life by the new rules of manufacturing that come with Additive Manufacturing Technology. General Electric (GE) believes that the future of manufacturing lies in Additive Manufacturing and is investing in technologies that would enable it to generate these new and radical designs, Methods like Topology Optimization have shown potential to come up with the radical designs that can be manufactured additively.
Almost all commercially available topology optimization tools use the same mathematical methods viz. Simplified Isotropic Penalization Material with Penalization (SIMP) and Level Set Methods to do their optimization. While these methods offer new designs, they doesn't explore the design space completely to give out a truly optimal solution. IISc and GE intends to explore other methods such as topological derivatives to obtain a truly optimal solution.
Output geometry that come out of topology optimization are often not drawing-ready nor are manufacturable. A lot of manual effort and time is spent in cleaning the model. 3rd party software like NX, ANSYS are already offering rudimentary solutions where the output geometry can be cleaned in a quasi-automated way. But this software primarily repair the geometry rather than create a new, clean and optimal one. Iso-geometric analysis is a new approach wherein a new usable geometry is recreated using Non-Uniform Rational Basis Spline (NURBS) approach which is the standard in most commercial CAD packages. GE, in collaboration with IISc, intends to leverage this approach on recreating a fresh new geometry based on the output given out by topology optimizers rather than just repairing the existing output geometry. GE believes this approach could significantly reduce the design cycle time.
Additional value addition can be obtained when topological derivative method is combined with the Iso-Geometric Analysis approach in a single framework. A single framework which combines the design constraints from topology optimization with the geometry constraints of iso-geometric analysis and additive manufacturing constraints would enable an end-to-end solution when it comes to design components for additive manufacturing. Design requirements are given at one end of the process and a multi-disciplinary set of constraints are taken together with internal feedback amongst topological derivatives, iso-geometry analysis and additive requirements through an overall optimizer to obtain the final drawing-ready design
A multi-disciplinary optimization setup that the combines topology optimization, geometry recreation and additive manufacturing has the potential to realize the benefits of reduced cycle time and improved efficiencies of power generation products.

Background and motivation (not exceeding 500 words)

Most of our design philosophies are constrained by the limitations of conventional manufacturing. Design that meet all our requirements cannot be brought to reality due to the limitations in casting and forging technologies. Even when they are manufacturable, there is lot of wastage of raw material during the manufacturing process. With long gestation periods in setting up the manufacturing plant, changes in design would mean changing the manufacturing setup which could be both cost and time exorbitant. Additive manufacturing is a solution for all the three problems. Pretty much any design is manufacturable additively, there is minimal to almost no wastage of material and the setup remains the same even with drastic design changes.
With these benefits of additive manufacturing we need to revisit the methods that gave out radical designs but were simply not manufacturable using the conventional methods. We are now able to manufacture these new designs and GE would like a relook at these methods.
Topology optimization methods have existed for the last three to four decades. The biggest problem with topology optimization was that its final outputs were simply not manufacturable. Various commercial organizations, research institutes and universities have tried to mitigate the problem by developing a variety of techniques. The most popular ones being SIMP and Level Set Methods. But this truly doesn't explore the full design space. To get a truly optimal solution, one needs to explore the full design space and we believe topological derivative could be one such method. The topological derivative is, conceptually, a derivative of a shape functional with respect to infinitesimal changes in its topology, such as adding an infinitesimal hole or crack. When used in higher dimensions than one, the term topological gradient is also used to name the first-order term of the topological asymptotic expansion, dealing only with infinitesimal singular domain perturbations. Research has shown that topological derivatives gives better results compared to level set method when it comes to identification of hole nucleation sites.
GE and IISc together would like to explore and commercialize the use of topological derivative method which has shown potential of offering superior results. A major challenge with topology optimization is that its outputs are not drawing-ready. There is still a lot of manual effort required to clean up the model. Typically, topology optimized models would be finite element models since most of the design constraints can be realized only in the finite element (FE) world. The optimized finite element model is exported as a CAD compatible geometry. Often, these exported CAD compatible geometries are jagged and lack aesthetics. CAD engineers would need to repair these geometries based on their experience and geometric design requirements. The cleaned-up geometry would then need to be sent back to the FE world to check if they meet the finite element design constraints are met. This would involve re-meshing and re-application of the loads and boundary conditions. Only when these constraints are met, one can say that the design is good and can be taken forward. If the design requirements are not met, another iteration with the CAD engineer is necessary. There can potentially be a few iterations before the final design is ready. This feedback loop involves FE engineers and CAD engineers working in tandem. So, this operation takes a lot of man hours before the final design is out. Since this process takes a major chunk of time in the design cycle, any effort in reducing this time is very much appreciated. Iso-geometric analysis approach shows potential in reducing this operation time. Iso-geometric analysis is a recently developed computational approach that offers the possibility of integrating finite element analysis (FEA) into conventional NURBS-based CAD design tools. Currently, it is necessary to convert data between CAD and FEA packages to analyze new designs during development, a difficult task since the computational geometric approach for each is different. Iso-geometric analysis employs complex NURBS geometry (the basis of most CAD packages) in the FEA application directly. This allows models to be designed, tested and adjusted in one go, using a common data set thereby reducing the operation time and obtaining improved and more accurate geometry.
The new rules of Additive Manufacturing also need to be incorporated while designing the final geometry using Iso-geometric analysis. So, we are looking at diverse design constraints viz. FE constraints, CAD constraints and Additive Manufacturing constraints and we are presently addressing them in silos. An optimal solution can be obtained only when they are tackled in one go. The solution is to have a multi-disciplinary optimization problem setup that encompasses these constraints, our final design requirements as objectives and internal feedback amongst the three disciplines in single framework. This approach would significantly reduce the design cycle time and give us a truly optimal solution which would include improved efficiencies of our power generators.

Project outcomes (please list specific objectives): *The project should address a specific need of the industry/industries and there should be clear expected outcomes from the project. It is expected that joint patents will result from this project.*

Objectives
1. An optimized design of a Heat Exchanger of a GE Power Generator needs to be additively printed. The optimized design would be created using the topological derivative that would be developed under this proposal.
2. The design output from the above method would be recreated to make it drawing ready by using the Iso-Geometry analysis method that would be developed under this proposal.
3. An integrated simulation framework would be created that would be used the solve the multi-disciplinary optimization problem that includes the above two methods viz. topological derivatives and iso-geometry analysis, design constraints from the finite element and geometry world along with the objective of reducing the weight of the Heat Exchanger while meeting the modal (frequency) requirements. The optimization problem would include additive manufacturing constraints as well. The larger objective is to use this simulation framework for optimizing other parts of the power generators as well.
4. Additively manufacture the part at IISc's and GE's facilities
5. Collate a list of best practices for additively manufacturing industry grade components.

The potential benefits that would accrue to GE from this project include
1. Reducing the weight of heat exchanger by offering a new design which would increase the overall fuel efficiency of the power generator.
2. Reducing the number of separate parts in heat exchanger by printing one complex part thereby reducing the manufacturing costs
3. Reuse the integrated simulation framework for optimizing other components thereby reducing the design cycle time

Scope (not exceeding 1500 words): *The scope should clearly lay out the contributions of the academic partner and the industry partner.*

Technical Program Execution Plan
The entire program will be executed in three phases spread over 3 years, as described below.
Phase-1 Objectives:
Phase 1 of the program will include the development of the topological derivative and iso-geometric analysis method. The developed methods would be validated against standard test cases that would be jointly identified by GE and IISc. The metrics for validation would be provided by GE. The outcome from this phase are standalone methods that can be deployed by GE internally on other components in its portfolio of power generators.
The development of these two methods would be in two sub-phases. With the first sub-phase being the mathematical formulation of the method and the second sub-phase being the actual implementation of the method using a combination of programming tools, analysis tools and CAD tools. The choice of the tools to be used for implementation would be jointly agreed upon by GE and IISc. The idea is to ensure that the methods are portable to be used within GE environment for other design optimizations.

It is also proposed that the validation of the methods would take place both at IISc and GE to ensure that the methods are environment neutral. The proposed methods should meet Technology Readiness Level (TRL) 2 requirements.
GE would jointly work with IISc to suitably modify the Heat Exchanger model, quantify the high-level design requirements and constraints such that it is compatible with the methods that would be developed.
Contributions from GE would include
1. Provision of test cases to test the feasibility of the methods that would be developed
2. Establishment of metrics to validate the topological derivative method
3. Establishment of metrics to validate the iso-geometric analysis method
4. Definition of design constraints and objectives
5. Decide on the platform to be used for implementation
6. Approve the developed methods viz. topological derivatives and iso-geometry analysis
7. Modification of the Heat Exchanger model as per IISc requirements

Contributions from IISc would include
1. Acceptance of the test cases
2. Acceptance of the design constraints and objectives
3. Acceptance of the modified Heat Exchanger model
4. Mathematical formulation of the topological derivative method
5. Mathematical formulation of the iso-geometry analysis method
6. Offer options of platforms for implementation
7. Implementation of the topological derivative method
8. Implementation of the iso-geometric analysis method
9. Testing and validation of the methods viz. topological derivative method and iso-geometric analysis method

Phase 2 Objectives:
Phase 2 of the program will involve the development of the integrated simulation framework that would enable multi-disciplinary optimization. Post validation of the two methods developed in Phase 1, the next major objective is to integrate both into a single framework and use the framework to solve the high-level requirement of weight reduction of the Heat Exchanger via a multi-disciplinary optimization problem.
We have design constraints from the finite element world that were solved using the topological derivative method. Geometry constraints were solved using the iso-geometry analysis method. In addition, the additive manufacturing constraints need to be considered to ensure the manufacturability of the component. Solution from one of this silo would have impact on the other silos. So, to ensure feasibility of the final solution, there must be feedback amongst all these silos. In other words, there must be no FE silo or CAD silo or Additive silo. All the design constraints must be brought together. An overall multi-disciplinary optimization problem needs to be setup that includes all these constraints along with the high-level design objective of weight reduction. To solve this optimization problem, we would a single platform that would bring in the two methods developed, the additive requirements and ensure that there is feedback amongst them. This is possible only with the development of an integration framework.
IISc would formulate the optimization problem based on GE's requirements. GE and IISc would jointly decide on whether to use 3rd party integration tools (with suitable modifications) or build the framework from scratch. IISc would then build the integration framework to solve the optimization problem. GE would provide appropriate test cases to validate the robustness of the framework. This objective from this phase is to have a framework that could be used for different components with different design objectives and constraints. This phase will lead to a recommendation of a concept meeting TRL3 requirements.
Contributions from GE would include
1. Establishment of metrics to validate the integrated framework
2. Provision of test cases for validation of the framework
3. Approval of the optimization problem formulated
4. Approval of the tool used to build the integration framework
5. Testing and validation of the framework in GE environment
6. Review of the optimal solution of the Heat Exchanger given out by the framework
Contributions from IISc would include
1. Formulation of the multi-disciplinary optimization problem for the Heat Exchanger
2. Offer options on the different kinds of optimization methods that would-be part of the integration framework and one that would be used to solve the multi-disciplinary optimization problem
3. Building of the integration framework
4. Testing and Validation of the framework in IISc environment
5. Using the framework to solve the optimization problem for the Heat Exchanger
6. Providing an optimal design of the Heat Exchanger

Phase 3 Objectives:
Phase 3 of the program would involve manufacturing the optimized Heat Exchanger using the 3D printing facilities available in IISc and if required, facilities in GE could be used as well. We should have an optimized Heat Exchanger that meets the defined design requirements manufactured by the end of this phase.
Since this is a new area in manufacturing, GE and IISc believe that there would be many key learnings from this exercise. One of the objectives from this phase is to collate all the best practices for additive manufacturing and incorporate them into the simulation integration framework built in Phase 2. So, this could potentially involve modifications to the two methods developed, modification and/or addition to the additive manufacturing constraints and modifications to the integration framework to ensure that it robust enough to handle additive manufacturing requirements for other parts.
Contributions from GE would include
1. Testing and validating the part manufactured additively as per design requirements
2. Provision of GE's 3D printing facilities if need arises
3. Collation of best practices and learnings from additive manufacturing
4. Identify additional test cases to leverage the newly developed methods and framework
Contributions from IISc would include
1. 3D printing of the GE test case in IISc 3D printing facility
2. Testing and validation of the design requirements for the Heat Exchanger
3. Collation of learnings and best practices from additive manufacturing

Work Packages and Timeline (use tables/Gantt charts): *The key tasks must be listed in the form of work packages with timeline (start and end month from the date of start of the project) and identify who will hold the prime responsibility for each work package and where the works will be conducted.*

Sl No	Activity	Owner	MONTH
1	TOPOLOGICAL DERIVATIVE - Mathematical formulation of method	IISc	**MON1-3**
2	TOPOLOGICAL DERIVATIVE - Modification of Heat Exchanger	GE	**MON4**
3	TOPOLOGICAL DERIVATIVE - Quantification of constraints and objectives	GE	**MON4**
4	TOPOLOGICAL DERIVATIVE - Establishment of metrics for validation	GE	**MON4**
5	TOPOLOGICAL DERIVATIVE - Implementation of the method	IISc	**MON5-8**
6	TOPOLOGICAL DERIVATIVE - Testing and validation of the method	IISc	**MON9**
7	TOPOLOGICAL DERIVATIVE - Optimization of Heat Exchanger	IISc	**MON9-10**
8	**PHASE1 DELIVERABLE - TOPLOGICAL DERIVATIVE METHOD**	**IISc**	**MON10**
9	ISO-GEOMTERY ANALYSIS - Mathematical formulation of method	IISc	**MON11-13**
10	ISO-GEOMTERY ANALYSIS - Establishment of metrics for validation	GE	**MON14**
11	ISO-GEOMTERY ANALYSIS - Implementation of the method	IISc	**MON15-18**
12	ISO-GEOMTERY ANALYSIS - Testing and validation of the method	IISc	**MON19**
13	ISO-GEOMETRY ANALYSIS - Recreation of Heat Exchanger Geometry	IISc	**MON20-21**
14	**PHASE1 DELIVERABLE - ISO-GEOMTERY ANALYSIS METHOD**	**IISc**	**MON21**
15	ADDITIVE DESIGN RULES - Definition of rules	IISc &GE	**MON22**
16	SYSTEM INTEGRATION - Finalization of tool for development	IISc	**MON23**
17	SYSTEM INTEGRATION - Establishment of metrics for validation	GE	**MON23**
18	SYSTEM INTEGRATION - Formulation of multi-disciplinary optimization problem	IISc	**MON24**
19	SYSTEM INTEGRATION - Building the integration framework	IISc	**MON25-26**
20	SYSTEM INTEGRATION - Testing and validation of the framework	IISc	**MON27**
21	SYSTEM INTEGRATION - Optimzation of the Heat Exchanger	IISc	**MON28-29**
22	**PHASE2 DELIVERABLE - SIMULATION INTEGRATION FRAMEWORK**	**IISc**	**MON29**
23	PROTOTYPING - Printing the part in IISc	IISc	**MON30**
24	PROTOTYPING - Printing the part in GE	GE	**MON30**
25	ADDITIVE DESIGN RULES - Collation of best practices	IISc & GE	**MON31-32**
26	**PHASE3 DELIVERABLE - ADDITIVE BEST PRACTICES REPORT OUT**	**IISc**	**MON32**
27	TOPOLOGICAL DERIVATIVE - Fine tuning the method	IISc	**MON33-35**
28	ISO-GEOMETRY ANALYSIS - Fine tuning the method	IISc	**MON33-35**
29	ADDITIVE DESIGN RULES - Fine tuning the constraints	IISc	**MON33-35**
30	SYSTEM INTEGRATION - Fine tuning the framework	IISc	**MON33-35**
31	PROTOTYPING - Printing the part in IISc	IISc	**MON36**
32	PROTOTYPING - Printing the part in GE	GE	**MON36**
33	**PHASE3 DELIVERABLE - PRINTED HEAT EXCHANGER**	**IISc**	**MON37**
34	**PHASE3 DELIVERABLE - FINAL REPORT OUT**	**IISc**	**MON37**

Key Milestones (six monthly): *List the key six monthly milestones.*

Following are key six monthly milestones:
1. Year 1, first six months: Formulation of topological derivative method
2. Year 1, second six months: Delivery of the topological derivative method and used to optimize the Heat Exchanger
3. Year 2, first six months: Formulation of the iso-geometry analysis method
4. Year 2, second six months: Delivery of the iso-geometry analysis method and used to recreate the Heat Exchanger
5. Year 3, first six months: Delivery of the Simulation Integration Framework and optimized, drawing ready Heat Exchanger
6. Year 3, second six months – 3D Printing of the drawing ready, optimized Heat Exchanger

Plan for commercialization (not exceeding 500 words): *The industry partner should show a clear path to commercialization if the proposed work is successful. (letter/communication from the industry partner may be scanned and uploaded)*

The outcome from the exercise carried out jointly by GE and IISc, will be a demonstration of the "proof of concept", a.k.a. Technology Readiness Level 3 (TRL3). A reduction in the weight of the Heat Exchanger would have a direct impact on the performance and fuel of the power generator. The exact quantification of the numbers would be determined based on the value of the weight reduction which will be known at the end of this exercise.
GE has a pipeline of power generator components that is targeted for weight reduction. The simulation integration framework could be deployed on these components of GE's power generation products which could yield lighter components in reduced design cycle time.
It will provide us a multidisciplinary optimization framework that could be deployed on various components of power generation products. The tests carried out, will provide us with insights into key design levers, and the path for modifying the concept.
It is envisioned that GE will pursue for productionization of the technology by maturing the technology through TRL6 and 9, subject to continually viable business and commercial environment.

Benefit to partnering academic institution: *(Please address each of the following items, briefly)*

a) Does the proposal promote innovation in areas that are directly of relevance to industry? Please describe briefly. (not exceeding 250 words)

1. First of a kind of topology method that radically improves the design
2. First of a kind geometry cleanup method by recreating the geometry rather than just tweaking the jagged geometry
3. First of a kind framework that integrates multiple disciplines viz. optimization, finite element, CAD, system integration and additive manufacturing
4. Collation of best practices for design when using the new age technology of additive manufacturing

b) Is the project proposing coordinated R&D between academia and the industry? If so, please describe. (not exceeding 250 words)

GE brings in the expertise of design requirements and metrics to ascertain the quality of methods developed, whereas Indian Institute of Science brings in the expertise of method development. Given the challenges in developing these first of a kind methods and integrating on to a single framework, a coordinated effort from GE and Indian Institute of Science is the most efficient way to advance this technology. Early phase of method development would require refinement of design requirement and validation of the methodologies. These needs require GE to partner with IISc to leverage the resources available to rapidly demonstrate the feasibility of the concept. GE will bring in the expertise in manufacturing the hardware, and the industry level expertise in designing the concepts, that need to be tested, and guide the concept development through the phase of the program.

c) Does the project strengthen the laboratories and research facilities at IIT or the Industry? (not exceeding 250 words)

This program will utilize computation and 3D-Printing facilities available at IISc. Since the current facility is limited, this proposal aims at investing in upgrading the facility to bring in additional computational facilities and 3D printers. This increased capability will strengthen the existing lab facility, and will equip IISc to address emerging industry problems in additive manufacturing.

Publications / patents relevant to the proposal: *List separately (a) publications/patents of PIs, and (b) publications of others, that are relevant to the proposed project. Restrict to relevant publications (ten maximum)*

(a1) Publications of IISc PI

(1) Frecker, M., Ananthasuresh, G.K., Nishiwaki, S., Kikuchi, N., and Kota, S., "Topological Synthesis of Compliant Mechanisms Using Multi-Criteria Optimization," Journal of Mechanical Design, Trans. ASME, Vol. 119, No. 2, June 1997, pp. 238-245.

(2) Saxena, A. and Ananthasuresh, G.K., "On an Optimal Property of Compliant Topologies," Structural and Multidisciplinary Optimization, Vol. 19, No. 1, 2000, pp. 36-49.

(3) Saxena, A. and Ananthasuresh, G.K., "Topology Synthesis of Compliant Mechanisms for Nonlinear Force-Deflection and Curved Path Specifications," Journal of Mechanical Design, Trans. ASME, Vol. 123, No. 1, March 2001, pp. 33-42.

(4) Saxena, A. and Ananthasuresh, G.K., "Topology Optimization of Compliant Mechanisms with Strength Considerations," Mechanics of Structures and Machines, 29 (2001), pp. 199-222.

(5) Yin, L. and Ananthasuresh, G.K., "Topology Optimization of Compliant Mechanisms with Multiple Materials Using a Peak Function Material Interpolation Scheme," Structural and Multidisciplinary Optimization, Vol. 23, No. 1, 2001, pp. 49-62.

(6) Yin, L. and Ananthasuresh, G.K., "A Novel Topology Design Scheme for the Multi-physics Problems of Electro-Thermally Actuated Compliant Micromechanisms," Sensors and Actuators, A Physical, 97-98(2002), pp. 599-609.

(7) Yin, L. and Ananthasuresh, G.K., "Design of Distributed Compliant Mechanisms," Mechanics Based Design of Structures and Machines, Vol. 31, No. 2, 2003, pp. 151-179.

(8) Mankame, N. and Ananthasuresh, G.K., "Topology Synthesis of Electro-Thermal-Compliant Mechanisms Using Line Elements," Structural and Multidisciplinary Optimization, 26(2004), pp. 209-218.

(9) Yin, L., Ananthasuresh, G.K., and Eder, J., "Optimal Design of a Cam-Flexure Clamp," Finite Elements in Analysis and Design, 40 (2004), pp. 1157-1173.

(10) Qian, Z. and Ananthasuresh, G.K., "An Optimal Embedding Problem in Topology Optimization," Mechanics-based Design of Machines and Structures, 32(2), 2004, pp. 165-193.

(11) Mankame, N. and Ananthasuresh, G.K., "A Novel Compliant Mechanism for Converting Reciprocating Translation into Enclosing Curved Paths," Journal of Mechanical Design. 126(4), 2004, pp. 667-672.

(12) Mankame, N. and Ananthasuresh, G.K., "Topology Optimization for Synthesis of Contact-aided Compliant Mechanisms using Regularized Contact Modeling," Computers and Structures, 82(15-16), 2004, pp. 1267-1290.

(13) Pedersen, C. B. W., Fleck, N. A. and Ananthasuresh, G. K., "Design of a Compliant Mechanism to Modify an Actuator Characteristic to Deliver a Constant Output Force," Journal of Mechanical Design, 128(5), 2006, pp. 1101-1112.

(14) Mankame, N. D. and Ananthasuresh, G. K., "Synthesis of contact-aided compliant mechanisms for non-smooth path generation," International Journal of Numerical Methods in Engineering, 69 (12), 2007, pp. 2564-2605.

(15) Rakshit, S. and Ananthasuresh, G. K., "Simultaneous material selection and geometry design of statically determinate trusses using continuous optimization," Structural and Multidisciplinary Optimization, 35 (2008), pp. 55-68, DOI 10.1007/s00158-007-0116-4.

(16) Sangamesh R. Deepak, M. Dinesh, Deepak Sahu and G.K. Ananthasuresh, "A Comparative Study of the Formulations and Benchmark Problems for the Topology Optimization of Compliant Mechanisms," ASME Journal of Mechanisms and Robotics, Vol. 1, No. 1, 2008, pp. 20-27.

(17) Sundaram, M., Limaye, P., and Ananathasuresh, G. K., "Design of Conjugate and Conjoined Shapes and Tilings using Topology Optimization," Structural and Multidisciplinary Optimization, Vol. 45(1), pp. 65-81, 2012.

(a2) Publications of GE PIs

18) Shamik Chaudhuri, Kalyanmoy Deb: An interactive evolutionary multi-objective optimization and decision making procedure. Appl. Soft Comput. 10(2): 496-511 (2010)

19) Kalyanmoy Deb, Kaisa Miettinen, Shamik Chaudhuri: Toward an Estimation of Nadir Objective Vector Using a Hybrid of Evolutionary and Local Search Approaches. IEEE Trans. Evolutionary Computation 14(6): 821-841 (2010)

20) Muthu Naveen, Shankar Jayaraman, Vinay Ramanath, Shamik Chaudhuri:
Modified Levenberg Marquardt Algorithm for Inverse Problems. SEAL 2010: 623-632

21) Kalyanmoy Deb, Abbadi Raji Reddy, Shamik Chaudhuri: A Reliable Classification of Gene Clusters for Cancer Samples Using a Hybrid Multi-Objective Evolutionary Procedure. Analysis of Biological Data: A Soft Computing Approach 2007: 231-257

22) Kalyanmoy Deb, Shamik Chaudhuri: I-MODE: An Interactive Multi-objective Optimization and Decision-Making Using Evolutionary Methods. EMO 2006: 788-802

23) Kalyanmoy Deb, Shamik Chaudhuri, Kaisa Miettinen: Towards estimating nadir objective vector using evolutionary approaches. GECCO 2006: 643-650

24) Kalyanmoy Deb, Shamik Chaudhuri: I-EMO: An Interactive Evolutionary Multi-objective Optimization Tool. PReMI 2005: 690-695

(b) Publications of others

1. Cinthia Gomes Lopes, Renatha Batista dos Santos, Antonio André Novotny., "Topological derivative-based topology optimization of structures subject to multiple load-cases," Latin American Journal of Solids and Structures.
2. Antonio André Novotny, Jan Sokołowski, W.M., "Topological Derivatives in Shape Optimization," Springer Publications.
3. TJR Hughes, JA Cottrell, Y Bazilevs, "Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement", Journal of Computer Methods in Applied Mechanics and Engineering, pg 4135-4195

Budget : *The project proposal can cover the following:*

a) The cost of hiring high quality manpower (in case not available in the institution).
b) Cost of procuring essential equipment if not available.
c) Maintenance/consumables and all such expenditure that is needed to run the experiments.
d) Cost of collaboration/consultations required for the project.
e) 30% institutional overhead charges.

Duration of the Project (to be restricted to a max of 3 years) : 3

Year-wise Budget Requirement (Rs. in Lakhs)

	Year 1		Year 2		Year 3 & 3+	
	Total Support	Industry Support	Total Support	Industry Support	Total Support	Industry Support
Manpower	12.00	6.00	12.00	6.00	12.00	6.00
Equipment	10.00	0.00	0.00	0.00	6.00	0.00
Consumables	0.00	0.00	4.20	0.00	6.15	0.00
Consultants	2.00	2.00	2.00	0.10	3.00	3.00
Overheads	9.90	3.30	9.90	3.30	9.90	3.30
Total	33.90	11.30	28.10	9.40	37.05	12.30
Industry share in%*		33%		33%		33%

*to be minimum 25% of total support each year

Budget (Rs.in lakhs): Total support : 99.05
Industry support: 33.00
% Ind. support : 33%

Specify the proposal budget under all the heads shown above. There must be a minimum of 25% industry contribution (in total, last row), primarily in sub---head (a) manpower and (d) Consultants stated above. Balance will be funded under this Yojana.

Specify the payment schedule/milestones by industry, if any. Contributions from MHRD/ Ministries will typically follow the same payment schedule with proportionate releases of funds. MHRD may set its independent milestones for release of funds if warranted.

First installment by GE at the beginning of the first year: Rs. 11.30 lakhs
Second installment by GE at the beginning of the second year: Rs. 9.4 lakhs
Third installment by GE at the beginning of the third year: Rs. 12.3 lakhs

If the proposed budget is to be split among more than one IIT, please split the budget under every head separately for each IIT component---wise and in percentage, as below. The overheads will be split pro---rata based on the total for each IIT.

	Lead IIT	Participating IIT (1)	Participating IIT (2)	Participating IIT (3)	Total
Manpower	100%	0%	0%	0%	100%
Equipment	100%	0%	0%	0%	100%
Consumables	100%	0%	0%	0%	100%
Consultants	100%	0%	0%	0%	100%
Total	100%	0%	0%	0%	100%