SOME REMINISCENCES ABOUT THE GROWTH OF IEOR INTERDISCIPLINARY PROGRAM AT IIT BOMBAY

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Formally the interdisciplinary program in IEOR, including initially the MTech-IEOR degree program to begin with, began at IIT Bombay in July 1976, i.e. in the academic year 1976-77. Academic activity in IE & OR area had initially begun first in the Mechanical Engg Dept, pioneered by Professor K.P.K. Nair during 1965-70, from whom I took my first courses in Industrial Engg and Operations Research in 1967-68 in my last year of the B.Tech program. Starting from late 1960's, some faculty from Mathematics department, particularly Professors M.N. Vartak and M.N. Gopalan, were involved in teaching a number of courses in Statistics, Design of Experiments and Combinatorics, and Deterministic and Stochastic Models of O.R. From Chemical Engg Department, Professor K.P. Madhavan was involved strongly in Optimization in Chemical Engg domain. Faculty from Humanities department were involved in teaching some courses such as Principles of Management apart from courses in Economics and Finance.

As of December 1975, when I joined IIT Bombay, the institute was actually actively considering starting an interdisciplinary M.Tech Program in Industrial Management, and a large interdisciplinary faculty committee was already involved in that effort; and I also was made a member of that committee. It did seem to me, however, that time was not quite ripe right then for starting an interdisciplinary program in Industrial Management at IIT Bombay. I suggested to our Director, Professor A.K. De, that if the institute was interested in starting an MTech program in I.E. & O.R., I would be glad to give a proposal for that, and with participation of some faculty from Mechanical Engg to begin with and with some cooperation from and interaction with some faculty from Mathematics, Chemical Engg, Electrical Engg, Humanities & Social Sciences Dept, an interdisciplinary MTech program in IEOR could be started right away. Professor De encouraged me to give a proposal, which I gave in December 1975. Subsequently, with additional inputs from faculty from an interdisciplinary committee, including wholehearted cooperation especially from Professors S. Somasundaram and R.C. Chaturvedi from Mech Engg, Professors M.N. Vartak and M.N Gopalan from Mathematics department, Professor K.P.Madhavan from Chemical Engg Department and from some other colleagues.

The proposal was finalized and cleared by the Senate in spring of 1976, and we launched the MTech-IEOR program in July 1976. The program was headquartered naturally in Mechanical

Engg department, which already had courses, running for its own students, B.Tech as well as M.Tech, such as Production Planning and Control, Production Management and Industrial Engineering. It must be acknowledged that Mechanical Engg department's leadership including Professor Sukhatme and several other senior faculty, had a quite far sighted and sufficiently liberal outlook which helped me over the following years to steer, along with several cooperative colleagues, the IEOR interdisciplinary program with good academic freedom, and in doing justice to both theory and applications. Over time it turned out, two decades later in 1995-1996, that in the starting of the DD-CIM program of Mechanical Engg Dept, contributions from Mechanical Engg and IEOR areas were both crucially important. But that was, as of 1976-77, a long long way off in the future and anything of that type was not at all in any one's imagination as such as of 1976-77. The next two decades turned out to be certainly very challenging for the IEOR program.

At the end of the academic year 1976-77, factually I was the only faculty in the institute in IEOR proper, and that was under the Mechanical Department. Three other faculty related to IEOR who were there when the IEOR program was cleared in the Senate in spring 1976, had left during the academic year 1976-77; some had joined IIMs and some at NITIE. In a way, this type of possibility could not be said to be totally unexpected. In fact even at the time of starting the IEOR interdisciplinary program, one of the questions posed by the all-India experts' committee that examined the IEOR program proposal, was whether there was at all a need for starting an M.Tech program in IEOR at IIT Bombay given the fact that there was a whole full fledged Central Government institution, NITIE, with almost two dozen faculty, devoted solely to Industrial Engineering right next door, i.e. across Powai lake. It is also well known that faculty related to O.R. can have fine prospects in schools of management. Nevertheless, I did have a strong faith in the field of IE & OR and was determined to do everything possible within my capacities, and the program did grow at a moderate and increasing pace through its first five years without any serious hindrance as such. It was verily an acid test.

It took, on my part, apart from guiding an average of five MTech IEOR students per year, teaching on an average five full-semester courses per academic year right from the academic year 1976-77 to 1980-81; by which time it had become evident that the possibility of infant-mortality of the M.Tech program in IEOR was no longer there. The range of courses I taught in those first five academic years itself included the following thirteen courses: 1) Network Models and Applications, 2) Applied Integer Programming, 3) Facilities Planning, 4) Methods Engineering, 5) Industrial Engineering (being compulsory for B.Tech-Mechanical), 6) Information Flow Systems, 7) Digital Systems Simulation, 8) Quality Reliability and Maintenance, 9) Selected Applications of O.R. in Industries, 10) Design and Analysis of Experiments, 11) Queuing Theory and Applications (PhD level course – IE801), 12) Quantitative Analysis in Finance and Marketing, 13) Operations Management (for Industrial

Management M.Tech program that had started in 1980-81). Such a reasonably wide spectrum of courses, offered and taught, made it possible for MTech IEOR program to attract bachelor of engineering students from several engineering disciplines, such as Mechanical, Electrical, Chemical, Civil, Metallurgical and so on. It also helped and made it possible to attract at least some more faculty.

Between 1977 and 1980, not less than three other interdisciplinary courses had started at the institute and faculty crunch was felt in all of them; and it was just not possible for IEOR program to depend on any other department's faculty to teach any courses for IEOR program. Each IDP had to struggle on its own. Despite the breadth of courses, which was critical for laying a broad foundation for IEOR program, for definitely protecting its long term prospects, I was particular to see that depth in courses was not sacrificed. Incidentally, an M.Tech student from IEOR 1978-80 batch who did his MTech project under my guidance in the area of Time Series Analysis, went ahead to do PhD at Univ. of Texas at Austin under a very well known faculty.

In all the courses right from 1976 onwards, as a matter of personal policy, I gave open-book exams in all my courses and students were expected to understand algorithms very thoroughly. I always covered everything from first principles, as my teachers at IIT and Cornell had done. Actually in the very preamble in the proposal for the IEOR program in 1976, it was made clear, among the program objectives, that "students in the IEOR M.Tech program are expected to understand not only how algorithms work, but also are expected to have a good understanding of what goes on while algorithms are applied in solving problems". Very often, algorithms are designed based on certain models that extract only a part of the reality in real life problems; and that necessitates some modifications while actually implementing solutions computed from computationally efficient algorithms in the real life situations.

So also, many times several algorithms are helpful in addressing certain kinds of real life problems, and a clear understanding of the meaning and underlying principles and approaches behind the algorithms is very important to know if one is to make effective use of the algorithms in addressing problems faced in real life in industry. These aspects are naturally very important since the field of O.R. has evolved very largely as a problem oriented discipline; and in fact in different decades different technologies do come up and often different ways of doing business and such things give birth to different kinds of problems in industry, different kinds of models and different concerns and so on; and understanding of things at a fundamental level is crucially important in looking for and relating algorithms to real life problems. Therefore keeping in mind long term prospects, depth in courses was encouraged in IEOR courses right from the very beginning.

The first PhD course in IEOR, IE801 – Queuing Theory and Applications, was taught in autumn semester of 1980; and I taught that for only one PhD student, who belonged to Mathematics department; even though it was to be a fifth course in that academic year for me. With substantial course loads already announced in IEOR program, it was not feasible for me to start more PhD level courses in IEOR at that time. While I was on the PhD committees and served as examiner for several PhD students in Mathematics Department consistently from 1977 till 1984, it was not really feasible or realistic to attract students for PhD from Mathematics department post their MSc in Maths in those days, for various reasons. Lack of PhD courses on the one hand and on the other hand the lack of faculty were the two sides of the usual "chicken or eggs first" paradox faced by IEOR program.

My research interests then in Markov Decision Theory, Queuing Systems and Optimal Control of Queues and so on, were quite alien to the majority of PhD students that could be taken through Mechanical Engg department and through Manufacturing Group of Mech Engg department to which I belonged. In fact, the first two PhD students that I guided came though the QIP scheme for engineering college teachers, and were admitted through Mechanical Department Manufacturing Group only, in 1979 and 1983 respectively.

It was only around 1985 that QIP program could create even a single seat for PhD in IEOR at IIT Bombay, and this could happen some five years after GATE Exam had a Paper in Production and industrial Engg since 1980-81. Thus for admitting PhD students in IEOR area, admission through Mechanical Engg department Manufacturing Group was the only practical available route in the first decade of the IEOR interdisciplinary program. Of course that implied whatever were the associated constraints. In 1986, a student who had done M.Tech from IIT Bombay Reliability Engg interdisciplinary program, preferred to do PhD under IEOR program and then did his PhD under the IEOR Program under my guidance under IEOR IDP. This gives a glimpse into the general picture about very severe and practical difficulties faced in the path of IEOR-PhD program in the first ten years of IEOR IDP.

While GATE Exams started in 1980-81, birth of the JAM Exam for BSc in sciences, Mathematics and Statistics and so on, was a long way into the future, as it turned out; and that happened only about 25 years after start of GATE. Recognition of the need for clear and wide opening of opportunities for the graduates of sciences and Mathematics into some branches of Engineering and Technology, and in a way diffusing the very hard dividing lines between sciences and engineering, took quite some time in our country. Subsequently, it turned out that starting an MSc-PhD program in IEOR was feasible only after IEOR area had about half a dozen faculty, and with strong interests in mathematics. That part of the IEOR IDP story comes later. As a matter of fact, it took fully the first 20 years of IEOR IDP existence to grow from a faculty strength of just 1 in IEOR in 1977 to 4 in 1997; which happened when Prof. N.

Hemachandra joined us from IISc Bangalore; and he subsequently played, with fine cooperation from other IEOR faculty, a very crucial role in starting the MSc-PhD program of IEOR with input of students through JAM exam. That roughly is roughly the basic timeline before the starting of MSc-PhD program in IEOR. Now about developments from 1980 till late 1990's.

By 1980-81, it was apparent that IEOR M.Tech program had struck strong roots and with sufficient diversity; and that made it slightly easier to attract faculty, even though for prospective faculty related to O.R. area, established Management Schools were generally seen as greener pastures as compared to joining in a very small and fledgling IEOR Interdisciplinary Program. In July semester of 1981 when Prof. A. Subash Babu joined us in Mechanical Engg department, having done his PhD under Professor Prem Vrat who was the pioneering figure in O.R. area at IIT Delhi, that meant literally a 100% increase in faculty strength for us here in IEOR area. In the decades to follow, Professor Subash Babu consistently made many valuable contributions in the growth of IEOR interdisciplinary program; and very particularly through his courses in Manufacturing Planning & Control and Quality Reliability & Maintenance and several others, and guiding a large number of PhDs in IEOR area.

It may be noted that since late 1970's, Management area was growing in India at a far faster rate than Operations Research. In fact, while as of 1960's at least a few large companies such as Hindustan Lever did have O.R. groups, such groups were generally closed down before mid 1970's. Air India had a very small and partly OR-related group as of 1976. Apart from ORG at Baroda, which was heavily into Marketing Research area and so on, there was no visible and well known O.R. Group in Indian industry. DRDO of course had a strong OR group, led by the legendary stalwart Dr. N.K. Jaiswal; but that was quite apart from things in industry as such.

Since the starting of the interdisciplinary MTech program in Industrial Management in 1980, for the next almost 15 years there were then, as a matter of fact, serious queries within the institute once every few years as to whether the very small IEOR program should simply wind up and merge into Industrial Management IDP. My strong faith in the field of IEOR did not permit my conscience to do anything other than putting in all possible effort to keep the IEOR program strong enough and relevant and also in tune with contemporary developments in each succeeding decade as far as I could; i.e. in some sense to keep the IEOR program 'ever-green' so to say. Fortunately, I was not entirely alone in this. Apart from myself, Professor Subash Babu who joined us in 1981 also had strong faith in IEOR area. I must acknowledge important contribution in 1980's by Prof. Hirjee Nagarwalla who joined us in IEOR IDP in 1982. He had done B.Tech in Chemical Engineering from IIT Bombay and M.S. in Industrial Engg from University of Wisconsin at Madison before joining us in 1982. His joining us in 1982 meant a 33.33% increase in faculty strength in IEOR area proper. He was the first IEOR Core faculty. He

was a very enthusiastic and enterprising faculty who took the initiative in starting a course on Stochastic Models around 1983-84 under IEOR IDP; something that was not feasible earlier due to lack of faculty strength in IEOR. He did his PhD under IEOR IDP, in the area of Reliability, under guidance of Professor Gopalan from Mathematics department. Professor Nagarwalla was with us until 1990, at which time he started his own consulting company. Apart from being keen in pursuit of theory, he was very knowledgeable in many kinds of computational matters also in real life problem solving situations. He made an important contribution in sustenance and growth of IEOR in the 1980's decade. Subsequently, it turned out, that he served as an Adjunct Professor jointly for SOM and IEOR at IIT Bombay in late 1990s'. That comes later.

Incidentally, in the Industrial Management IDP started in 1980, an example of a contribution from IEOR IDP side was that their course on Marketing Research (IM609) whose syllabus I had written myself at the time of the IDP proposal, I taught for the first time, in the academic year 1981-82, using reputed Texts as of then and of course a very considerable part concerning Multivariate Analysis starting fully right from fundamental textbooks on Multivariate Analysis. After that from the next year onwards a faculty from Mathematics who was on the Industrial management IDP committee, taught that course for some years. Now a few words about several things that had to be kept in mind while working for the growth of the IEOR program from 1981 onwards, that is starting after the initial crucial five years were safely crossed.

At this point it may be noted, as students of IEOR field are also very much aware, that unlike conventional branches of engineering, the IEOR field does not have its own hardware technology, as other engineering branches such as Mech / Chem / EE / Computer Science & Engg have; and moreover essentially the IEOR area is generally a 'staff' function rather than a 'line' function in industries, playing essentially the role of an internal consultant. Consequently, in placement of IEOR M.Techs in industry, their area of engineering at UG level is fairly often at least partially correlated with the industry they join, unless it is for example a software company as such. Consequently, quite often M.Tech students, barring exception of very brilliant students, may tend to prefer working on M.Tech project topics that may be at least somewhat related or relevant to their UG engineering discipline if that is possible. From the point view of the M.Tech IEOR program also, at an institute of technology such as IIT, it is important or helpful, as an interdisciplinary program, and since the field of IEOR itself is interdisciplinary, to have some reasonable 'bridges' or linkages or interactions with at least some other branches and departments of engineering.

Since a fundamental purpose in IEOR field and in its consultative role in industries, is to often improve or sometimes design afresh systems for various functionalities, correspondingly a certain level of awareness of domain knowledge in the area of application becomes often extremely important. Therefore in teaching of application area courses for IEOR students, it is

very helpful if faculty can project not only an in depth knowledge of algorithms, models and computational approaches, but also the overall perspective of the problem area in the domain of application and where in the spectrum of the already known and existing methodologies in use in that domain the new methods and approaches and algorithms being taught stand. Also, especially in the context of B.Tech students of IIT, who often do venture to take many courses from mathematics and computer science departments for learning a variety of algorithms, their taking IEOR courses as such has often an expectation of not only learning algorithms and related theory as such, but also the learning about the overall setup or framework in industry where they can be gainfully applied.

In many application oriented subjects in IEOR, which is by nature a problem oriented field, it is often the case that no single textbook covers the things on algorithmic side in depth and also projecting a comprehensive perspective of things and practices in the associated underlying application areas. This aspect needs to be kept in mind by faculty teaching application area oriented courses in IEOR. At times this can involve considerable additional readings from some textbooks and literature from the related branch of engineering or technology. Another aspect in application oriented courses is that in some areas at least the dynamics of change in industries evolves at a very fast rate; e.g. in the area which since the last three decades is known as Supply Chain Management and which actually covers an extremely vast ground in industries and deals with entire multi echelon convergent-divergent material flow systems in manufacturing and distribution with numerous stages of value addition as well as transportation.

Since the 1970's in almost every decade vast changes have occurred in this field, and it is always important to keep the course offerings in this area with adequate contemporary relevance apart from advances in algorithms per se. Although some books with the title including the phrase 'Supply Chain Management' are very much there, in any well developed interdisciplinary program in IEOR, just a single course in Supply Chain Management is just far too inadequate to deal with the serious issues and significant problems involved in the vast spectrum of problems that may be construed to come under the broad umbrella called as SCM. A little more about this will be said later.

The oil prices crisis that precipitated in 1973, when the price of crude oil being controlled by a global oil cartel shot up by more than 150% within just a couple of months, had a huge impact on the power industries in 1970's and that in turn led to huge upheavals in the auto industry as well starting in late 1970's. Some Auto giants in US came on the verge of bankruptcy around 1978-79 due to unbeatable competition from Japanese auto industry's small, compact, efficient and economic cars; and which were produced using very versatile and lean manufacturing planning and control systems too. Starting in 1980, literally hundreds of

research papers appeared in IEOR and management related journals comparing the apparently-simple ‘paperless’ and largely decentralized JIT-Kanban or ‘Toyota’ systems with mainframe-computer driven and significantly centralized production flow control systems prevalent very much then in the western countries, and also considering development of newer alternatives. Pioneering researches and a host of ingenious new strategies were developed at MIT, Cornell and elsewhere such as Hierarchical Planning, Cyclic Planning Systems and so on. The Japanese advances included not only ‘software’ changes in production-inventory planning and control but also certain associated and crucially important ‘hardware’ kind of changes in their auto companies and others.

The Japanese systems had more elements of feedback control on a micro time scale and feed-forward control only on a much larger time scale. Full blown closed form analytic solutions of the Japanese JIT-Kanban systems were practically infeasible and uneconomical due to very serious computational tractability issues as the associated Queuing Networks were of very notorious varieties. To convey to students in depth, starting from first principles, what was going on in the fierce battles in production-inventory flow control in the American versus the Japanese systems required covering really a lot of ground which no single text could book cover, and teaching had to be based very largely on large number of original research papers only. Still it was considered to be a solemn responsibility to let our B.Tech, M.Tech, and some PhD students what “in the world” was actually going on and what and how much could be seen in a ‘unified’ view of things. While the battles were being fiercely fought, and partially evaluated, between the Americans and the Japanese, the Germans had refused to go whole hog with either the American systems or those of the Japanese. They were ingeniously developing their own ‘Load Oriented Manufacturing Control’ strategies and systems. After all, leaders cannot be followers!

Things in industries in India in 1980’s were lagging many decades behind in respect of all these developments in US, Japan, Germany and so on on. Interestingly from an O.R. viewpoint, The decade of 1980’s saw many pioneering works at the Wharton School of Management, Rochester School of Management, IBM and so on, which brought together in synergistic ways, after almost two decades, judicious combinations of techniques from Queuing Theory, Batch Sizing Inventories, Scheduling Theory, Queuing Networks and so on. Such developments underscored very much the need in IEOR programs for not only in-depth coverage of many techniques relating to these distinct areas but also educating students well about how these subjects and fields can come together on the battleground of addressing real life problems in industrial scenarios in large scale systems. Whereas Stanford, Cornell and some other top notch schools for many decades had separate courses on Scheduling Theory, Inventory Theory and at some places even on Inventory Theory in Distribution Systems as such, in India, as far as I have been aware, IIT Bombay IEOR program was probably the only program in India

which has had separate courses in Scheduling Theory and inventory Theory right from 1981 onwards running continuously.

The decade of 1980's was a very 'happening' decade in terms of real life applicable pioneering developments in Scheduling, Inventory and Queuing systems. Correspondingly, deliverables in the courses on Inventory and Scheduling were naturally revised 'online' on a fast time scale, so to say, as a matter of serious academic responsibility. The developments in the realm of manufacturing systems became even more interesting when starting in late 1980's the Japanese pioneered in development of Flexible Manufacturing Systems (FMS) that combined certain economic advantages similar to those in large scale manufacturing systems together with some advantages of flexibilities in small scale production systems also. The FMS's were developed for a different and important segment of manufacturing industries, of a high tech type. In the changeover from large Job-Shop like scenarios to FMS's, many crucial hardware changes were also ingeniously done by the Japanese, permitting very small batch sizes and often even just a batch of 1.

In our IEOR interdisciplinary program at IIT Bombay I made every effort, through teaching of courses and guidance of student projects, to keep our B.Tech, M.Tech and some PhD students from Mechanical Engg Manufacturing area also, abreast of many advances in the above areas; and in spring semester of 1991 I started the course IE650: Modeling and Optimization in Flexible Manufacturing Systems. These systems being highly automated even in the context of material movements, using Fixtures and Automated Guided Vehicles, and having fast turnaround times, and so many aspects of Control of Queues are crucially important in them. In a sense, optimal design and management of FMS emerged as an area where really just about every technique of O.R. was potentially applicable in one way or another. It was an exciting era of new developments. Academic activities related to the Flexible Manufacturing Systems paved the way or provided a partial roadmap for some more developments in 1990s's also in our IEOR program and simultaneously in our Mechanical Engineering department also.

For at least about nearly 25 years, at our IIT I happened to be the only faculty with strong interest in Inventory theory plus scheduling theory plus queuing theory; although some other departments had faculty with interest in some of these areas. In well established schools of IEOR abroad, these three areas almost invariably have separate faculty as these areas are oceans in themselves. On the other hand in the practical reality in industries, Queuing, Inventories and Scheduling are often three perspective views of the same underlying reality. In practice in a very large fraction of instances, either a material waits for a machine or the machine waits for the material. Materials waiting at a machine constitute a work-in-process Inventory and is also at times looked upon a Queue. The Queuing viewpoint can address questions such as the statistical distribution of time spent by a piece of material waiting for a

machine or a processor; which can become important from the point of view of predicting the times for flow of the material through various queues, a question very meaningful for a 'customer' who has placed an order, one among many, for processing of the material through a number of stages of manufacturing, and important also from the point of view of dynamic flow control strategies in the system.

When management is concerned with the burden of interest on working capital locked up in work in process inventories, the problem comes in the domain of Inventory Theory and needs to be addressed from that viewpoint. For humans or automated systems that need to address the question of strategies for the Allocation of Processors or Machines to Tasks dynamically over time, the problem comes in the domain of Scheduling Theory. Thus, Scheduling Theory, Inventory Theory and Queuing Theory are all inextricably involved in getting the best out of complex production distribution systems. It is too well known that very significantly, "Wealth comes from Manufacturing"; and the world has seen how China and several other countries that were not at all wealthy as such 50 years ago are indeed rich today due to their tremendous strides in manufacturing. A decent and reasonably sized IEOR interdisciplinary program, in the long run, cannot afford to remain aloof from the realm of manufacturing. Even historically, over the last four decades probably at least 35-40% of the our M.Techs in IEOR have been employed in areas related to manufacturing and distribution in some way or another. With increasing computerization, automation, and integration in manufacturing systems, this percentage is not likely to come down.

At reputed schools such as Purdue University and many others, strong linkages have existed for decades between departments of IE and Mechanical Engineering. At our own IIT, the starting of the Dual Degree Program in Computer Integrated Manufacturing, from which we do still get even today a good number of students for Minor in IEOR, was an excellent example, of the interaction and synergy that was developed between Mechanical Engg and IEOR, over more than two decades starting in late 1970's. It remained very strong while IEOR faculty were associated with courses such as courses in FMS and so on. It is said departments generally have walls that demarcate them. If interaction among departments or IDPs is not significant, over time the walls seem quite pronounced also. In the interests of our significantly common student bodies, it is often helpful, especially for IDPs to have their faculty develop linkages with some other departments, for better synergy. It is very nice that currently such linkages exist between IEOR and EE and with Mathematics at least as far as I am aware. Some more linkages may help in future. Even within IEOR, it is helpful if faculty dealing with Optimization, Stochastic processes, Queuing, Scheduling and Resource Allocation, can have over the years a good interaction and collaboration in guidance of projects etc, so that students can get a holistic and richer view of the underlying realities in a range of problems faced in real life in

industries. Needless to say, this in the realm of manufacturing is not alienated from the crucially important national drive towards Make-in-India.

At this point I would like to mention my impression that in probably several subject areas in interdisciplinary programs that are not as saturated or too well set as firmly established purely mathematical subjects, teaching in interdisciplinary program courses can be far more demanding and basing a significant part of course teachings directly upon the evolving and contemporary research papers in the field can be rather unavoidable, if our teaching is to address significant live issues of real life applicability.

A very important development in 1990, for our IEOR IDP, was the joining of Professor Narayan Rangaraj in IEOR IDP. It is always a pleasure in itself, when a B.Tech from here, after doing PhD abroad at a reputed university, joins here as a faculty colleague. As a matter of fact Prof. Narayan, who had done B.Tech Mechanical from IITB Bombay and PhD in Non-differentiable Optimization from Johns Hopkins University, had the option of joining either the well established Mechanical Engineering Department of our IIT, or the IEOR IDP here which as of 1990 had only 2 faculty members in IEOR proper other than Prof. Nagarwalla who was about to leave in that year. Prof. Narayan joining us in 1990 under IOR IDP was a very helpful event and in a way also was an indication that IEOR area here had developed good roots and branches and would see better days ahead. Professor Narayan, over the years, even apart from his own individual contributions in teaching a variety of courses, through research and also specialized activities for the Indian Railways, has also played an important part in bringing together and maintaining a balance between a range of interests of faculty in IEOR IDP working in different realms.

At this point I would like to mention a few more interesting things that emerged after starting the course on Modeling and Optimization in Flexible Manufacturing Systems and teaching it every year from 1991 to 2002. When I began to teach the course in spring of 1991, there was not a single text book on FMS that could be considered appropriate for a self contained course on that topic as such from the point of view of students from IEOR, as opposed to Manufacturing Engineering students as such. There were of course dozens of excellent research papers in top notch journals related to addressing IEOR related problems in FMS, and I had to base the IEOR course on FMS largely on a selection of the research papers, and as usual covering partly different sets of papers in different years. It was a very pleasant experience for me, since the course content involved some good range of models of deterministic optimization, analysis of certain queuing systems and queuing networks, aspects of control of queuing systems, and in some systems the application of Markov decision processes and so on. Generally, students from Mechanical Engineering were in earlier years not too enthused about queuing theoretic models and so on. One of my teachers used to

say as of late 1960's that much of queuing theory was then hidden behind the 'Laplacian curtain'; after all, even in the simplest single server queue the transient behavior of the Number in the System is available in time domain only as an infinite series of Bessel's functions of the second kind. To my pleasant surprise, many good students from Mechanical Engineering department who were part of the student population in that FMS course, learned well the contents including queuing theoretic parts with good enthusiasm. Such was the impact of the wave of FMS in 1990's. In fact, one of the fine M.Tech students from Mechanical Engineering in Manufacturing in that course went straight ahead to do PhD at MIT.

Another interesting thing that happened in the course of teaching the course on Modeling and Optimization in Flexible Manufacturing Systems was the following. Professors Narahari and Vishwanadham's book on FMS came out around 1993 or so. After that I used to cover a few chapters from that book in my course on FMS, and still the rest very much from many research papers of pioneers directly from fine IEOR related journals themselves. In some email communication with Professor Narahari in 1995 I mentioned to him that I found their book on FMS quite useful and suitable for my students to a fair extent; and then we had some bit of technical discussion on a couple of fine points etc. That is when he mentioned to me that a couple of his PhD students would finish in about a year's time.

Essentially, the fact that in our IEOR interdisciplinary program we were serious about theory as well as applications, and with a good balance among the two, is what helped us to stabilize and grow. Very often I used to tell our students that firstly one must learn the available theory inside out and only after that ask what aspects of reality elude modeling in elegant and analytically tractable and computationally tractable models; and only then study the variations in exact approaches that can be made to handle certain more delicate aspects of the real problems; and one should not take the shortcut of seeing merely the simplistic approaches at the expense of underlying fundamental theory. It turned out that in September 1997 Professor N. Hemachandra joined our IEOR IDP; and so our faculty strength in IEOR then rose to 4, from 1 in July 1997. That was a long journey of full 20 years; and after that there was no looking back. That I must say was a real turning point in the evolution of IEOR IDP at our institute.

Incidentally, the occurrence of queries in the institute, about our IEOR program either growing 'faster' or else merging with School of Management that started in 1994, or with Mathematics Department, or with Systems and Control group, continued relentlessly and periodically from early 1990's also till about 2005 or so. In early 1990's an idea also was under preliminary consideration, to start a separate Department of Interdisciplinary Studies, with its own Head of Department; but very soon that was not seen to be a value adding proposition, and the theme that 'small is beautiful' did prevail. It is understood that in the IIT statutes Departments

have a permanency and status above IDPs and IDPs are fundamentally looked upon more as temporary academic structures even though for academic purposes as such the IDPs have full academic autonomy.

So every five years or so, such queries about the dissolution or merging of IDPs has been a fact of life for all IDPs. Some IDPs got wound up in 15 years, and some in about 25 years even though they had produced not less than 25 PhDs, partly because their scope was not broad enough and their M.Techs faced difficulties in getting jobs. These things or facts of reality I am mentioning here because they are probably relevant also to the aspect of future planning on the part of IEOR IDP. For an IDP, producing many PhDs is always certainly commendable but may not have always been sufficient, as per past experience. Interestingly, if one looks at the list of Departments, Centres and IDPS at our institute today as compared to what it was say 2-3 decades ago, the number of Departments as well as Centres has gone up very considerably, while the number of IDPS has definitely shrunk.

Through the couple of decades starting in 1990's, I devoted considerable effort in strengthening the IEOR program in its interface with AI and this was also helpful in simultaneously strengthening the interface of the V year Integrated Program of Mech Engg Department with Manufacturing Engineering specialization with AI, and in the launching in 1996 and subsequent development of the Dual Degree Program in Computer Integrated Manufacturing with significant contribution from IEOR side. I was formally and fully a faculty of Mechanical Engg Department and felt an equal commitment for the advancement of Mechanical Engineering Department no less than the advancement of IEOR program also. In fact, my involvement in AI started very naturally in both my commitments, to Mechanical Engineering department and to the IEOR IDP.

Incidentally, the increasing and significant involvement and activities in IEOR IDP, in terms of substantial course offerings as well as several dozen M.Tech projects in IEOR dealing with addressing some interesting O.R. related problems using AI methods, also helped to keep at bay any attempts in the institute towards persuasion for simple submergence of IEOR area faculty under the School of Management; since AI is fundamentally far closer to Operations Research than Management per se. In fact, there is nothing in any definition of Operations Research to say that Operations Research, in solving real life problems, cannot use methods that have grown in the ambience of AI such as methods drawn from fields such as Mathematics, Computer Science, Statistics, Physics, Optimization, Stochastic Search, all of which arc fields or areas from which Operations Research community has very freely drawn from and used them judiciously over time. I did of course have to pay a heavy price for the diversification of growth of IEOR activities towards AI, in that from the academic year 1994-95 till 2006-07, i.e. for a period of as much as 12 consecutive years, I taught on the average 4.5 full

semester courses per year; but it surely was a gainful and mind expanding experience for me as well. Now a bit about how all that happened in a way quite naturally.

The 1990's was a very interesting time period wen AI was very widely noticed. Works in 1980's such as Hopfield neural networks and many others had left behind the apparent 'AI-winter' that was said to be there in the preceding decade or two. Russell & Norvig in their classic textbook on Artificial Intelligence observed that in the 1990 Iraq war, just about 25 days of logistics planning by US armed forces using AI techniques, involving nearly 50,000 'vehicles', including tanks ships and so on, had paid off for nearly 25 years of investment by DARPA in AI-related sponsored projects in US. In the battleground of real life problem solving, and also in the action-field of computing inside computer systems, O.R., C.S. and A.I., all these coexist and shared a good deal of commonalities and complementarities. In the decades of 1950's and 1960's, many interesting optimization problems of a combinatorial nature attacked by typical O.R. methods had run into rough weather more often than not; and William Maxwell, who wrote the widely noted textbook 'Theory of Scheduling' in 1967, had in his preface included a line expressing a tinge of disappointment, saying that although many great minds of the day had tried their hand at some challenging scheduling problems they had mostly "essentially returned rather empty-handed."

On the other hand, I recall one of my teachers in late 1960's saying that as of then some serious thinkers in the O.R. community were seriously wondering as to why the good old Simplex method of LP worked as well in practice as it did. The birth of the theory of NP-Completeness in 1971 and numerous related advances in Mathematical Programming in 1970's, had then thrown new and powerful beams of light on matters of computational tractability.

Subsequently, interest in probabilistic methods and stochastic search methods even for solving purely deterministic problems had naturally become very serious and more widely acceptable. Also, in solving problems of a combinatorial nature, in the realm of Computer Science, various attempts were under way to do 'computing' involving Boolean rather than numeric variables. Languages such as Prolog and LISP were being widely used in Planning Problems and Optimal Path or Motion-Sequence problems. Through 1980's, microprocessors and far faster computing speeds and birth of the PC, had made a sea change in the realm and ambience of computing for solving real life problems. In 1990's there was increasing activity on the interface of O.R. and A.I.. In the realm of some typical combinatorial problems in O.R., the symmetric Traveling Salesman Problem was no longer considered as formidable, with deft use of Mathematical Programming advances; while Job Shop Scheduling Problem was a much harder nut to crack and process of solution of a 10 job and 10 machines Job Shop scheduling problem instance from the 1963 book of Muth and Thomson, had a long trajectory over time

that included a ray of hope through work of Adams and Balas at CMU in 1987, and subsequent confirmation of an optimal solution, that happened to be in fact found but not confirmable in the work Adams and Balas in 1987, by Carlier and Pinson in France in 1989. Starting In 1991, Japanese authors were attacking Job Shop Scheduling by Genetic Algorithms, while others were attacking it by Neural Networks also.

Seemingly unrelated methods were competing on the battleground of many problems where up to 1970's mostly O.R. methods of Mathematical programming were talked about most often. At our IIT, even some B.Tech students of Mechanical Engineering Department as of early 1990's had become very curious and keen to understand how Neural Networks as well as Neuro-Fuzzy Systems were being shown to solve simply stated but definitely interesting problems such as Automatic Controller for Backing up a Truck-and-Trailer system up to a designated parking dock location. Automated Learning in AI systems was a subject that aroused the interest of may IIT students from Mechanical Engineering as well as IEOR.

Methodologies such as Reinforcement Learning and Bayesian Decision Networks were being employed for certain 'Learning' and 'Localization' problems in the context of mobile robots. Methods of Self Organizing Map type of Neural Networks were being applied to Group Technology problems for more effective Production Control strategies in large Job Shops; in an area that was traditionally considered to be a typical work area for Production Engineering and Industrial Engineering. In the realm of Motion Planning problems for robots, and for cranes and hoists and so on, use of AI based planning methods were widely reported in many classic textbooks on AI and said to be effective practically. Certain kinds of Search Problems for Optimal-Paths for Motion Planning by Agents were being 'seen' in some computing paradigms as Theorem-proving Problems and attacked accordingly. Languages such as Prolog, based on Predicate Calculus, and LISP, rooted in Lambda-Calculus, were in wide use in AI labs in the context of such problems. In short it was apparent starting in early 1990's that AI was making strong inroads into many disciplines including Manufacturing engineering, Robotics, Industrial Engineering and Operations Research. Since I belonged to Mechanical Engg Manufacturing group and also IEOR, I was naturally very keen to understand how and where the competition by AI methods worked and stood.

With that kind of intensely interesting background of happenings since early 1990's, and cutting across many branches of engineering, mathematics, logic and computer science, arousing strong interest of even B.Tech and M.Tech students of Mechanical Engineering as well as M.Tech students in IEOR, I felt that it was indeed worthwhile to invest efforts into the strengthening of the IEOR program in its interface with Computing and also AI. It was not at all clear as to what ground in the realm of practical real life combinatorial problems arising in O.R. and attacked earlier by O.R. methods, may be yielded to A.I. methods.

So I decided to get involved in this area through teaching as well as guidance of M.Tech student projects in IEOR as well as students of DuaL Degree CIM program of Mechanical Engg. As always I was keen to take up everything from first principles only in the teaching. In the context of Programming, for decision systems with maximal flexibility I felt that our students must know and be able to implement things in C language as of then, since that language has the capacity to get down to things even at 'bit level', and provide maximal transparency as well as flexibility in experimenting with newer ideas or variations in algorithms, rather than simply depending on any ready made canned software packages and just 'playing' the game of the adjustment of some parameters in the canned program packages. That is how I started since 1994-95, to begin with, two Computational Labs under IEOR IDP, namely IE-681: Computational Lab in Object oriented Programming and Simulation and IE-682: Computational Lab in Database and Knowledge-based Systems.

Subsequently this was followed up by two full courses that I ran from 2003 until 2008 on two classic AI / CS subjects under IEOR IDP, namely IE702: Neural Networks and Fuzzy Systems and IE703: Knowledge Based Systems and Applications. That took me through a good number of renowned texts as well as papers on various related subjects from other fields of study, such as for example the Extended Kalman Filter Based Neural Networks, the Boltzmann Machine and so on. Everything in these courses I covered from first principles only. That was a gainful and mind expanding experience for me, and from mid '90's onwards several dozens of B.Tech-Mechanical, Dual Degree CIM, and M.Tech students in IEOR did their projects with me on quite a wide range of interesting topics relevant to Mechanical Engineering and / or IEOR.

I would like to note here that in a way, when our students go out of the gates of our institute after graduation and step into the real life world of industry, and when they are there to solve real life problems, neither do the real life problems come with any tag that bears the name of any technique or discipline of study nor does industry generally care too much about exactly what type of technique and approach or paradigm of modeling and computations is invoked, as long as the problem is solved adequately on real life data. Consequently, a richer and sharper perspective view of problems areas and the spectrum of potentially applicable techniques learned by students in a Master's degree program stands them in good stead in their career ahead. That is also a kind of feedback we receive from good students who have studied here decades ago also.

Personally my feeling over the years is that maintaining the interdisciplinary spirit of IEOR and the spirit of open inquiry and a reasonably wide perspective, apart from depth of courses, is also very important in the long run. Setting the algorithms, models and approaches in a proper perspective does help to serve well our students from B.Tech, Dual Degree, M.Tech, PhD and

occasionally SOM also who take our courses or do projects with us. In real life there are many issues and realities; and awareness about them is helpful to project a realistic view of whatever we do. These days, at times it may be felt that 'return on investment' of time spent on MTech students is generally much less than that on PhD students; since relatively very few M.Tech students are managing to write conference or journal papers. Yet care needs to be taken to see that M.Tech students do not feel alienated or less cared for. During the last decade, my impression is that the number of B.Tech students going abroad for PhD is again increasing slowly; and several B.Tech students from my classes in Inventory and Scheduling in the last 5-6 years have gone for PhD abroad to fine universities in the field of IEOR. Increasingly and naturally so with more and more globalization, expectations from our students are also apparently rising, and often these expectations also have an interdisciplinary angle in them.

Looking forward about our IEOR IDP, I do believe that with core faculty strength of IEOR about to reach and cross ten very soon, it is really probably time to give serious thought towards growing from the status of an IDP to become a full fledged department; which practically can boil down to starting a B.Tech program here in IE & OR. That could possibly be very much a part of the planning of the IEOR IDP for the coming five years. I do not consider the starting of a B.Tech program in IE & OR at IIT Bombay within next five years as totally impossible; although of course it mean a great lot of work and does imply a serious long term collective kind of unwritten commitment on the part of the faculty of IEOR IDP.

Interdisciplinary programs can mean more academic freedom and some benefits of the phenomenon of "small is beautiful"; but that also comes at a price. Starting new entities is challenging; and starting new entities in interdisciplinary realm is perhaps a bit more challenging. Becoming a department implies a lot in terms of commitment towards imparting a B.Tech education in I.E. & O.R., keeping in mind that the UG degree forms a strong educational foundation for a student and his years spent in earning the UG degree have a very long lasting impact on the student's career and thinking. Incidentally, for many decades even some top notch schools of IEOR in US had only about 15-16 faculty and were admitting of the order of ten PhD students every year.

At present, thanks to the initiation of the MSc-PhD program of IEOR pioneered by Professor Hemachandra and with active support from all the IEOR colleagues, and the addition of excellent faculty in IEOR in the last fifteen years, we have a very good core faculty strength now and covering a rich spectrum of areas of their activities, including for example: continuous and discrete optimization, stochastic processes, stochastic decision processes, game theory, stochastic differential equations, digital systems simulation, systems dynamics, queuing theory, optimal control, queuing and communication networks, artificial intelligence,

machine learning, transportation and logistics, supply chain management, operations research in fields such as railways, infrastructure, healthcare.

It is indeed a very impressive list of areas of strong expertise under the one roof of our IDP of IEOR. The advantages of starting a B.Tech program in IE & OR are very considerable for faculty, the department and the institute. B.Tech students have a very open mind to begin with and a department has a wonderful opportunity to mould things over three years and impart to the students a well rounded education, something that they would remember and gain from in many decades as they contribute to our country or to organizations wherever they go on the face of the earth and carrying with them the name of their graduating institute and department.

The name Industrial Engineering and Operations Research has served us well for the last 42 years and with a firm belief in the field as such and for several reasons that relate to things as of today or here-and-now also, I may put down some things that come to mind. The name Industrial Engineering is in a way equidistant from all branches of engineering and indirectly including the phrase IE in the department name conveys a clear signal that graduates of IE & OR department can contribute in industries making use of technology from practically any branch of engineering more or less.

From another angle, just as conventional branches of engineering at our institute are producing engineers as opposed to scientists, so would a department of IE & OR. It is often said that engineers make things, which includes also design of systems apart from products. So automatically, a good amount of emphasis would automatically come, in a B.Tech program in IE & OR, on the design of systems for flows of information and materials to a reasonable extent, for planning of systems that involve use of different types of resources such as machines, containers or vehicles, manpower and so on depending on the type of industry. Students in B.Tech in IE & OR could take a minor in another branch of engineering or mathematics and so on, depending on their interests. It might be desirable that some fraction of faculty in IEOR could be new young faculty that could be be added, who have strong linkages, in terms of either their basic degree or area of work, with some conventional branch of engineering; and correspondingly they could help strengthen the linkages of IEOR department with other departments and in applications of IEOR methodologies in industries relating to some specific conventional branches of engineering.

I recall that while formulating the Dual Degree Program of Mechanical Engineering Department in 1995-96, we had first undertaken a quite careful survey of existing comparable programs at reputed universities or institutions. A major effort of that kind could possibly be undertaken by IEOR IDP if it wishes to consider growing into a department of IEOR, covering

some well known departments abroad and those in India. Incidentally, while at a reputed university the phrase IE within its name stands for Information Engineering, since the last decade or so. I am not sure if that kind of major change in emphasis could be gainful for our IEOR IDP. In US, there are dozens of very good schools in IEOR area, the field is extremely mature and very advanced and very well known since last nearly six decades.

In India, very possibly a spelling of IE as Information Engineering in the acronym IEOR may most likely raise eyebrows from the field of Computer Science and Engineering. In fact, early in the decade starting in 2000, when Mathematics Department proposed an MSc program in Applied Statistics and Informatics, thee was a huge debate in the Senate regarding use of the name Informatics by Mathematics Department, and the Senate even asked Mathematics Department to reconsider its use of the term Informatics in its program title. Mathematics Department subsequently had to put in a lot of effort and it ultimately won in its naming of the new program exactly as it had proposed.

At this point I may revisit something that I had alluded to on the occasion of inauguration of our IEOR building in August of 2016. We can never forget the fact that our field of O.R. was born in war, namely WW-II, and that the biggest sponsors of IEOR research projects in many advanced countries have always been their defence establishments, even though we may not hear or read too much about that prominently too often. In this context I recall that in late 1990's, the legendary O.R. figure Dr. Professor N.K. Jaiswal who was Chief of O.R. at DRDO in Delhi, had in an open talk in late 1990's mentioned that even though India was not militarily involved in the 1990 Iraq war, India was seriously concerned about the potentially harmful impact on India, of large scale burning up of entire oil fields in Kuwait that was being done by Iraqi forces. At that time Indian government had directed the O.R. Group in DRDO to make a clear cut but fast assessment of the situation within 14 days, regarding any possible impact of the large scale Kuwait oilfields' burning on the weather or crops in India. Within 14 days, DRDO constituted and worked in an O.R. team that did the entire project, including data collection, modeling, simulation and so on, and informed the government of India that the impact of the oil field fires on India would be negligible. Wars do not occur too often; but when they do occur, stakes are on gigantic scales. Our country is aspiring to become a world power and that is necessary because otherwise other powers can easily thrust war upon our country. War problems are naturally highly unpredictable and interdisciplinary works are inevitable in things related to war. We may, sincerely, hope that our B.Tech program in IE & OR does turn up strongly and that in future some of our B.Techs in IE & OR could very well join some defence-related establishments of our country and make valuable contributions there over time. During the last four decades we have seen, though not very many, some Indian navy commanders, army colonels and so on coming to IIT Bombay IEOR M.Tech program as sponsored candidates. Any B.Techs in IEOR in some future years joining some defence related

establishments could possibly render a very valuable and long lasting service to our country indeed. If our IEOR field itself owes its birth to war efforts, then our IEOR program helping at some time in future our own defence forces in some ways and most significantly through potentially some B.Techs in IEOR joining some defence establishments, is something that is really worth pondering about. In crucial times such as war, the relevant metrics and constraints can be quite different as compared to those in leisurely peace times. Probably our younger faculty with all the more enthusiasm and long long bright years of career ahead form them, may really ponder over such questions also in the context of desirability of our IEOR IDP growing into an IEOR Department with its own B.Tech program in IEOR.

Only time would tell the shape of the future, and much depends upon the collective thinking and collective will of IEOR faculty, as to whether and when a B.Tech program in IEOR may start at our institute. To me at least that appears a most natural and very commendable way towards IEOR becoming a strong permanent entity rather than a transient entity that an IDP essentially is, at least as per the thinking at the institute over the decades so far.
In have just tried to put down very briefly and in a rather rambling manner perhaps, some thoughts that came to mind during last three weeks or so, after Professor Narayan suggested that I may do and share such a write up at this point in time. Whatever biases and shortcomings that must be there in what I have tried to write, may kindly be excused.

Above all I must most sincerely acknowledge, over the years as faculty member at our institute, the very fine and synergistic ambience at our institute, both in Mechanical Engineering Department and in IEOR IDP. It was a very gainful experience for me, with a lot to learn from colleagues over time, and really a very cherishable experience. Incidentally, both as a student of Mechanical Engg Department and as a faculty with office in Mechanical Engg Department, the inspiring arch carrying the emblem of our institute always stood next door. I am glad for the opportunity that I had for serving our institute, and owe very much to my teachers as well as to all the colleagues in Mechanical Engg Department as well as colleagues in IEOR. It has been really wonderful to see our IEOR IDP grow from strength to strength, and especially with so many young brilliant faculty joining which brings still stronger hopes.

With best regards to all,
Prakash Awate