1. PUBLISHABLE SUMMARY

Summary of the context and overall objectives of the project (For the final period, include the conclusions of the action)

Building upon the achievements of the Marie-Curie ITN Mixed-Integer Non-Linear Optimisation (MINO), the goal of MINOA was to train the next generation of highly qualified researchers and managers in applied mathematics, operations research and computer science that are able to face the modern challenges of European and international relevance in areas such as energy, logistics, engineering, natural sciences, and data analytics. Fourteen Early-Stage Researchers (ESRs) were trained through an innovative training programme based on individual research projects motivated by these applications that due to their high complexity will stimulate new developments in the field. The mathematical challenges can neither be met by using a single optimisation method alone nor isolated by single academic partners. As special challenges, the ESRs worked on dynamic aspects and optimisation in real time, optimisation under uncertainty, multilevel optimisation and noncommutativity in quantum computing. The ESRs devised new effective algorithms and computer implementations. They validated their methods for the applications with respect to metrics that they have defined. All ESRs derived recommendations, both for MINO applications and for the effectiveness of the novel methodologies. The ESRs belong to a new generation of highly-skilled researchers that strengthens Europe's human capital base in R&I in the fast growing field of mathematical optimisation. The ESR projects were pursued in joint supervision between experienced practitioners from leading European industries and optimisation experts, covering a wide range of scientific fields. This proved to be possible even in the pandemic.

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far (For the final period please include an overview of the results and their exploitation and dissemination)

We achieved our goals. We visited over 60 conferences and wrote 30 articles. Our training programme contributes to that: While our ESRs attended many courses (mathematically related but also language courses and complementary skill courses), we organised summer schools about machine learning, conic optimisation and nonlinear optimal control problems as well as their applications where not only our ESRs but researchers from the entire world were attending. We created a training network for early-stage researches from which not only the ESRs but the entire consortium and the entire European Research Area benefits. Our research results strongly extend and push the state of the art: The ESRs significantly contributed to their research area by tackling their respective application from a theoretical and practical point of view. Next to several workshops (like the ESR Days that were organised by the ESRs) and conferences, we also organised the international conference "Trends in Modelling, Simulation, and Optimisation: Theory and Applications" together with the German research center TRR154 that was attended by more than 200 academics and industrial representatives worldwide.

Progress beyond the state of the art, expected results until the end of the project and potential impacts (including the socio-economic impact and the wider societal implications of the project so far)

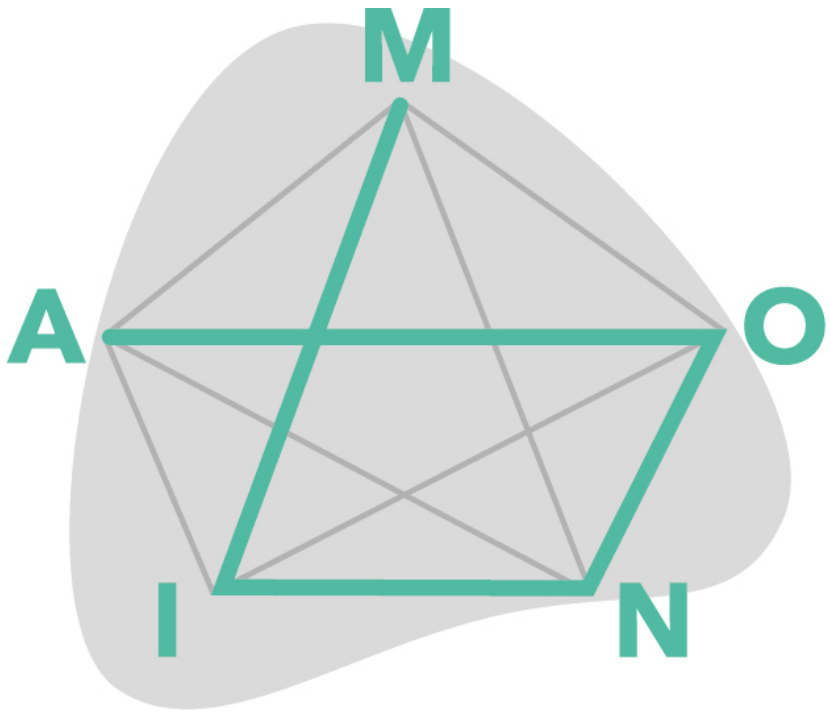
Innovative research was linked with international, interdisciplinary and intersectoral higher education: Our researchers have been trained to strengthening Europe's human capital base in R&I with a new generation of very entrepreneurial and highly-skilled ESRs. Already now it is clear that MINOA was able to train highly gifted top talents, as the ESRs have received top job offers both in academia as well as from industry. They have successfully completed their respective research projects. Throughout the project duration, the consortium participated in many conferences and our ESRs published articles in the top-tier journals of the field. This shows the success of the project. We tackled and extended the boundaries of recent mixed-integer mathematical optimisation, thus establishing a new state-of-art in this research area.We have researched novel approaches for complex decision-making in modern challenging applications for which practically efficient methodologies were not available. To this end, each ESR was assigned to at least two applications. They developed exact and approximate methods, reformulations and decomposition techniques and tractable relaxations. Based upon these, solution methods/implementations were derived. The ESRs have validated their results with respect to suitable metrics and gave recommendations about the usability of the methods for the respective application. Due to space restrictions, we only point out a few highlights, first for new methodologies. In mixed-integer optimal control, we developed new numerical methods or computing open-loop and feedback controls for problems with switched differential equations with a disjunctive programming approach. It was also possible to design an effective solution algorithm for optimal control problems with binary switches where the most relevant theoretical achievement is a full polyhedral description of the underlying switching structure on which the algorithm is based. For hedging against uncertainties, an effective algorithm could be designed and implemented for a class of problems in which costs are uncertain and second-stage decisions are mixed-integer convex. This was achieved by adjustable robustness and a Dantzig-Wolfe approach. When pushing the frontiers of challenging applications forward, we mention that for investigating the potential of modern quantum computers, D-Wave quantum solver results were compared with a newly developed randomized heuristic that showed better results. In large-scale combinatorial optimisation, an alternating direction method could be developed that is capable of tackling various large-scale semidefinite programs. Optimisation programs over graphs could be extended to higher-order hypergraphs, while also showing how such problems can be studied through analytic methods. In addition, an exact penalty method that first transforms a linearly constrained binary quadratic problem into a max-cut instance, and then solves the resulting instance effectively by semidefinite programming, was introduced. In energy management, the optimal power flow problem was studied in electricity networks under uncertainty in the nonconvex case. Results show a considerable risk of infeasibility even for relaxations. A pseudopolynomial separation routine could be developed for a challenging class of valid inequalities for the Direct Current Optimal Transmission Switching problem, for usage within global branch-and-cut approaches. It was possible to improve computational and analytical methods for symmetry reductions and their application to hard combinatorial problems. For enhancing methods in data analytics, in particular in network analysis and design, new methods for finding dense subgraphs could be developed. In logistics, an algorithmic solution framework for solving various integrated real-time public transport problems was presented and implemented. The aircraft deconfliction problem was investigated. New methodologies for the underlying bilevel optimisation problem could be presented for which novel reformulation approaches were developed.

With respect to the societal impact, MINOA has strengthened the links in the European Higher Education Area by structuring and strengthening the MINOA training capacity at the European level. In particular, MINOA has reinforced existing long term collaborations and has established new ones, not only within MINOA, between MINOA and other large-scale research initiatives, but especially at the ESR level and naturally by extending and training the skill set of our ESRs.

Address (URL) of the project's public website

https://minoa-itn.fau.de/

Full MINOA Logo



MINOA

MIXED-INTEGER NON-LINEAR OPTIMISATION: ALGORITHMS AND APPLICATIONS