Final report

1.1 Project details

Project title	Deltagelse I IEA EBC Annex 60, Modelica
Project identification (program abbrev. and file)	64013-0566
Name of the programme which has funded the project	Energieffektivitet
Project managing company/institution (name and address)	Danish Building Research Institute, A.C. Meyers Vænge 15, 2450 Copenhagen SW
Project partners	Danish Building Research Institute
CVR (central business register)	29102384
Date for submission	26-03-2018

1.2 Short description of project objective and results

IEA EBC Annex 60 aimed to develop and demonstrate new generation computational tools for building and community energy systems based on the non-proprietary Modelica modeling language and Functional Mockup Interface standards (FMI).
The objectives of the project were to:

- Develop open-source, freely available, documented, validated and verified computational tools that allow buildings, building systems and community energy grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand.

- Coordinate currently fragmented duplicative activities in modeling, simulation and optimization of building and community energy systems that are based on the Modelica and FMI standards.

- Create and validate tool-chains that link Building Information Models (BIM) to energy modelling, building simulation to controls design tools, and design tools to operational tools.

The project has achieved the following outputs:

- The Modelica **Annex60** library was developed. This work harmonized the previously fragmented and duplicative development of libraries, and resulted in a jointly developed library that is now used by four major Modelica libraries for building systems.

- Building and district energy simulation tools based on the FMI standard were developed. Within Annex 60, using the FMI standard as an Application Programming Interface (API) to different simulators allowed run-time coupling of various simulators.

- A mechanism was developed to transform a digital model of a building and its energy systems to Modelica code, which can then be readily used for advanced building performance simulation.

- Demonstration case studies showed how these technologies can be used for the design and operation of building and district energy systems. The case studies showed that very low energy systems and increased grid integration imposes structural changes to building and community energy modeling and simulation tools and processes.

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IEA-EBC Annex 60 havde til formål at udvikle og demonstrere en ny generation af beregningsværktøjer til bygnings- og samfundsenergisystemer baseret på det offentligt tilgængelige modelleringssprog Modelica og Functional Mockup Interface standarder (FMI).

Formålet med projektet var at:

- at udvikle open source, frit tilgængelige, dokumenterede, validerede og verificerede computerværktøjer, der gør det muligt at konstruere og betjene bygninger, bygningssystemer og energinet som integrerede, robuste, ydeevnebaserede systemer med lavt energiforbrug og lav spidsbelastningsbehov.

- at koordinere nutidens fragmenterede aktiviteter inden for modellering, simulering og optimering af bygnings- og samfundsenergisystemer baseret på Modelica og FMI standarder.

- at udvikle og validere en serie værktøjer, der knytter Building Information Models (BIM) til energimodellering, bygningssimulering til styringsværktøjer samt designværktøjer til driftsværktøjer.

Projektet har resulteret i:

- Modelica Annex 60 biblioteket er blevet udviklet. Dette arbejde harmoniserede den tidligere fragmenterede og ofte dublerede udvikling af biblioteker, og resulterede i et fælles udviklet bibliotek, der nu anvendes af fire store Modelica-biblioteker til byggesystemer.

- Bygnings- og distriktsenergisimuleringsværktøjer baseret på FMI-standarden er blevet udviklet. Inden for rammerne af Annex 60 og ved anvendelse af FMI-standarden som Application Programming Interface (API) til forskellige simulatorer, var det muligt at tilkoble forskellige simulatorer.

- En mekanisme er blevet udviklet til at omdanne en digital model af en bygning og dens energisystemer til Modelicakode, som derefter kan bruges umiddelbart til avanceret simulering af bygningens præstationer.

- Casestudier til demonstrationsbrug har vist, hvordan disse teknologier kan anvendes til udformning og drift af bygnings- og distriktsenergisystemer. Casestudierne viste, at lavenergisystemer og øget netværksintegration nødvendiggør strukturelle ændringer i bygnings- og samfundsenergimodellering og simuleringsværktøjer og processer.

1.3 Executive summary

The IEA EBC project *Annex 60: New Generation Computational Tools for Building & Community Energy Systems* led to open-source, freely available, documented, validated and verified new generation computational tools. These tools allow buildings and community energy grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand. The developed tools are all based on three non-proprietary, open standards:

- The Modelica modeling language for implementing models (https://www.modelica.org/),
- The Functional Mockup Interface (FMI) standards to couple simulators (https://www.fmi-standard.org/), and
- The Industry Foundation Classes (IFC) for building information modeling (http://www.buildingsmart-tech.org/) as well as other BIM-related standards such as Information Delivery Manual (IDM) and Model View Definitions (MVD).

Thus, Annex 60 committed to, leveraged and contributed to open standards that can be used with a variety of tools, rather than developed software technology that depends on the implementation of a single tool provider. This avoids vendor lock-in and provides to industry a stable basis, governed by standards, to invest in.
The target audience of Annex 60 is the building energy research community, design firms and energy service companies, equipment and tool manufacturers, as well as students in building energy-related sciences.

The IEA EBC Annex 60 was conducted from 2012 to 2017 through the collaboration of 42 institutes from 16 countries. The research phase of Annex 60 started on July 1, 2013. The Annex benefited from a strong organizational framework in order to coordinate work between the various researchers world-wide.

Annex 60 was organized in the subtasks and activities shown in Fig. 1. Subtasks 1 developed and implemented the software technology required by the applications. Subtask 2 was focused on validation, verification and demonstration of the developed software technology for building and community energy system design and operation. Subtask 3 was focused on dissemination of the results through special tracks at professional conferences, through training workshops and through publications in international scientific journals.
SBi/AAU contribution to Annex 60 was mainly related to activity 1.1 and 2.1, as described more in detail in section 1.5.
Danish participation in IEA Annex 60 was important with regards to the trends towards zero energy and electrification of the energy infrastructure that demands that buildings and district energy systems become increasingly integrated to reduce energy use, power density and to shift load.

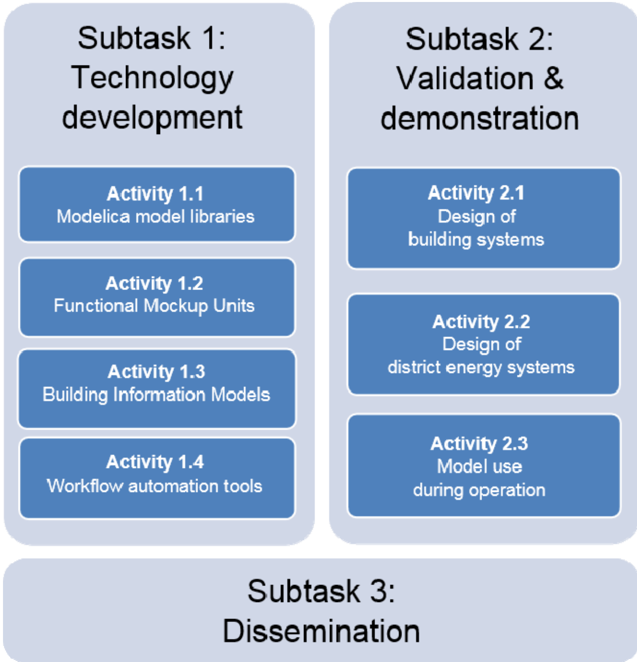

Figure 1:Structure and organization of Annex 60

This requires taking into account system-level interactions between building storage, HVAC systems and electrical and thermal grid. Such a system-level analysis requires multi-physics simulations and optimization using coupled thermal, electrical and control models.
Clearly, building simulation programs face new challenges to support such systems throughout the building life cycle. Existing building simulation programs have been developed for the use case of building energy performance assessment to support building design and energy policy development. Other use cases such as control design and verification, model use in support of operation, and multi-physics dynamic analysis that combines building, HVAC, electrical and control models were not priorities, nor even considered.
Therefore, Danish participation in IEA EBC Annex 60 was crucial in order for Denmark to be part of the development of the new generation of computational tools, which are needed to meet increasingly stringent energy performance targets and challenges posed by distributed renewable energy generation on the electrical and thermal distribution grid.

1.4 Project objectives

As buildings become increasingly integrated to reduce energy and peak power and to increase occupant health and productivity, new challenges are posed to engineers when using building simulation programs to support decision making during product development, building design, commissioning and operation. New requirements that were not yet recognized 20 to 40 years ago when the development of current building simulation programs started include:

- Model-based design of integrated building systems by design firms and of products by equipment and controls providers to optimize energy-efficiency and peak load, and to reduce time-to-market for components, systems and advanced control systems.

- Design processes based on a Building Information Model (BIM) which become increasingly used by design firms.

- Integrated design of building envelope, HVAC systems and control strategies by design firms.

- Model use to support operation, for control providers as part of an energy or smart-grid aware controller, for commissioning agents to provide a reference for the expected building operation, for fault detection and diagnostics providers to provide a reference model that can be used to classify fault signatures, and for urban planners and utility companies to develop design and operation strategies for energy grids with dispatchable distributed loads, generation and storage.

These applications require the integration of multiple domains (air-flow, thermodynamics, controls, indoor environmental quality, and electrical grid) and multiple disciplines (HVAC/energy consultant, architect, controls engineer, electrical engineer) that use a variety of tools that represent building systems across largely varying time scales from seconds to years and length scales from building components to urban districts. Next to the mentioned engineering consultancy services, the technology is as well important to the building simulation research community to build and deploy their R&D through standardized tools.

Figure 2 shows these new challenges that Annex 60 addressed through the use of a standardized modeling language, standardized Application Programming Interface (API) and standardized data models. In contrast to these new computational technologies, today's building simulation programs were primarily designed as tools for energy analysis. Use of these programs during operation is cumbersome, as is their integration with models from other tools, or with models created by other team members or discipline experts.
Furthermore, in today's building simulation programs, operational sequences are highly idealized. This prevents these tools from being used for the verification of the proper design and implementation of control sequences. It also makes it difficult to use the tools to analyze existing buildings which may have unconventional systems and control logic, because the original systems may have been retrofitted and buildings may have been re-purposed. Furthermore, current building energy performance simulation tools are not designed for the overall investigation of the interaction between buildings, district heating, cooling and electricity systems at the same time, which is required to evaluate new energy concepts that exploit dispatchable, distributed energy storage, generation and loads.

The ultimate goal of this Annex is to leverage, further develop as needed, deploy and demonstrate the use of modern modelling, simulation and analysis techniques that result in:

- Accelerated invention and deployment of integrated systems and performance-based solutions at the building and community level, at a reduced technical risk for early adopters, through a model based design and performance verification process.

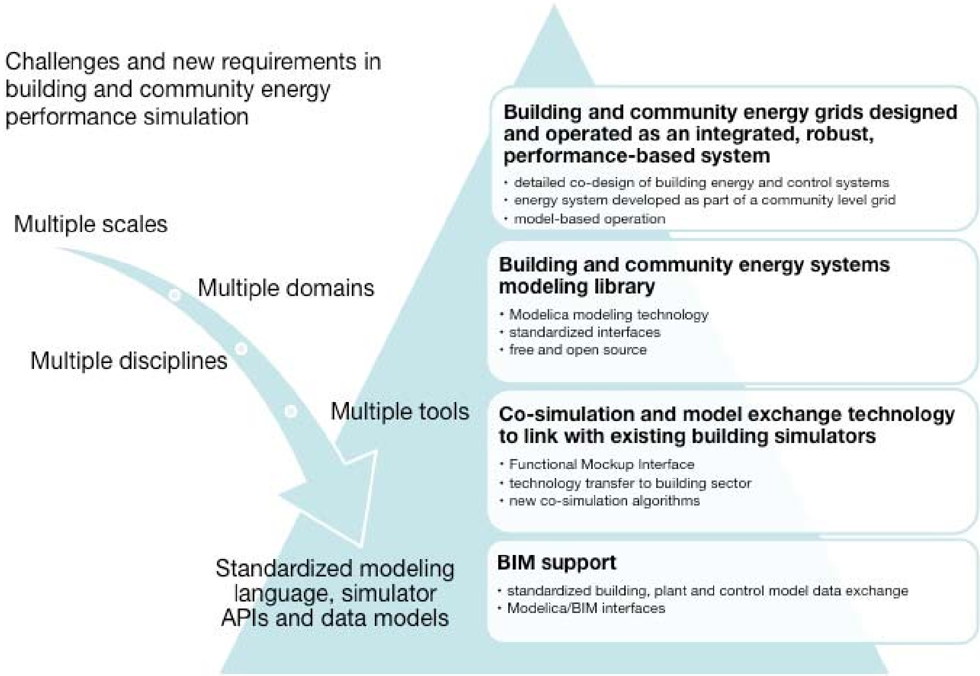

Figure 2: Overview of interrelation between technical challenges and outcomes of Annex 60

- Reuse of models across the whole building life cycle to ensure realization of design intent and persistence of energy savings, peak demand reduction and comfort through proper operation.

- Increase of system-level performance through more effective collaboration facilitated by interoperable models and simulators for the currently vertically separated disciplines: controls, thermal systems, daylighting, electrical systems and air quality.

During the research phase, eight international, semi-annual expert meetings were successfully held and most of the expert meetings were followed by technical workshops over multiple days:

- on March 11-12, 2013 at RWTH Aachen, Germany, during the planning phase (50 attendees),
- on August 23-24, 2013, in Aix-les-Bains, France (54 attendees),
- on March 8-9, 2013, in Lund, Sweden (50 attendees),
- on September 15, 16 and 17, 2014, in Berkeley, USA (50 attendees),
- on April 21 and 22, 2015, in Galway, Ireland (50 attendees),
- on September 16-18, 2015, in Leuven, Belgium (50 attendees),
- on May 9-11, 2016, in Miami, USA (30 attendees),
- on October 22-23, 2016, in Porticcio, France (65 attendees).

In order to synchronize work packages and activities, more than 120 coordination meetings and web conferences were conducted within the activities and among the leaders since the start of Annex 60. Minutes of these activities and meetings were continuously organized and disseminated using the Annex-internal *Bitbucket* repository system. The repository system, which included a wiki, was a key resource for organizing collaboration.

Figure 3: Expert meeting in Leuven, Belgium

1.5 Project results and dissemination of results

The main findings of each subtask are described in the following:

Subtask 1 - Technology Development

***Activity 1.1 Modelica model libraries**,* developed the Annex60 library, a free library that provides more than 300 classes (models, functions, etc.) for the development of Modelica libraries for building and community energy and control systems. Figure 4 shows an example of a HVAC system modelled with the Annex60 library.

The intent of the library is that classes of this library will be extended by implementations of Modelica libraries that are targeted to end-users. Major goals are to codify best practice and to provide a solid foundation onto which other libraries for building and community energy systems can be built, and to avoid a fragmentation of libraries that serve similar purpose but that cannot share models among each other, thereby duplicating efforts for model development and validation.

This library became the core of the four Modelica libraries:

- *AixLib*, developed by RWTH Aachen, Germany,
- *BuildingsSystems*, developed by UdK Berlin, Germany,
- *Buildings*, developed by Lawrence Berkeley National Laboratory, Berkeley, CA, USA, and
- *IDEAS*, developed by KU Leuven, Belgium.

Prior to the Annex, theses libraries had limited scope, were mutually incompatible, and in some cases not available to the public.

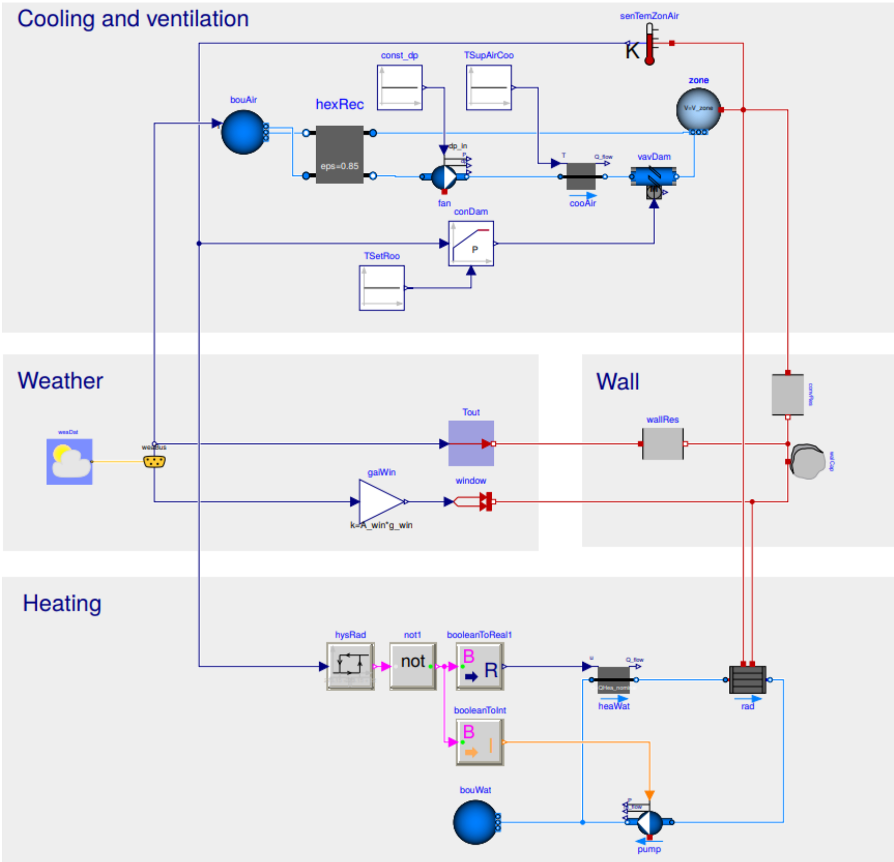

Figure 4: Example of HVAC system modelled with the Annex60 library

SBi/AAU contribution to this activity was related to the development of an active beam model in Modelica to be included in the Annex60 library. In particular, two models were developed: a model for cooling only, and a model for heating and cooling. These models can now be used by users to design innovative HVAC systems incorporating active beams as terminal units.

Activity 1.2 Co-simulation and model exchange through Functional Mockup Units, developed co-simulation and model-exchange interfaces in legacy building energy simulation programs and further developed middle-ware for co-simulation and model exchange. All work was based on the non-proprietary Functional Mockup Interface standard.

Activity 1.3 Building Information Models, developed BIM to Modelica translators. This was accomplished through the use and extension of the Open BIM data formats defined by the Industry Foundation Classes (IFC) and through the use of other BIM-standards such as the Information Delivery Manual (IDM) and through Model View Definitions (MVD). Figure 5 illustrates the process how to derive Modelica models from BIM. The architect and HVAC engineer use domain specific BIM-based CAD software and may export their models to an Industrial Foundation Classes (IFC) file (left side). This file is converted into SimXML which is the file format for SimModel, a data model for the simulation domain. SimModel extends information provided by IFC with simulation specific parameters. The SimXML file is then converted to a valid Modelica model with the software framework developed in this Annex. This framework is setup to support multiple Modelica libraries as well.

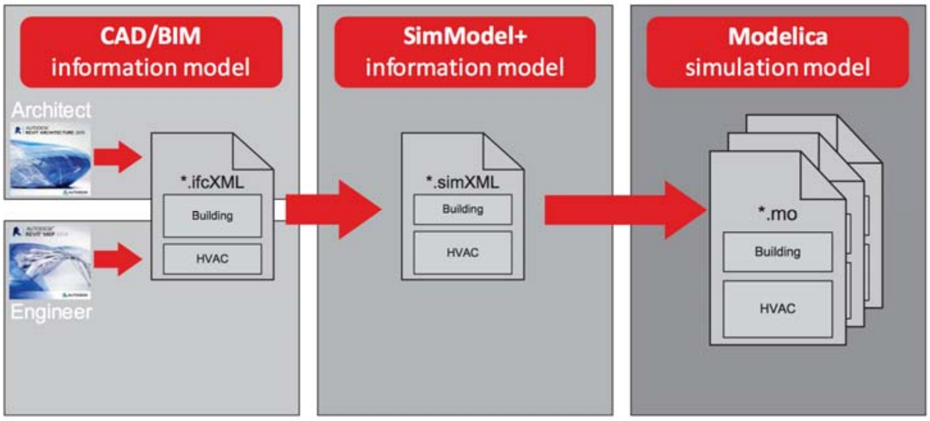

Figure 5 Overview of the transformation process from BIM to Modelica

Activity 1.4 Workflow automation tools, developed free open-source Python packages to automate the workflow of developing and using Modelica models.

Subtask 2 - Validation and Demonstration

Activity 2.1 Design of building systems, demonstrated how to design energy and control systems for buildings and how to size systems under consideration of diurnal weather patterns, energy storage and time-varying electricity prices of a smart grid.

A total of nine case studies are presented in which building energy simulation analysis and building energy design were performed based on existing Modelica libraries. The description of the difference case studies also demonstrates which advantages Modelica offers for building and plant simulation in comparison to other simulation tools and approaches.

SBi/AAU contribution to this activity was related to demonstrating how to design and model a novel HVAC system for simultaneous heating and cooling of office building using Modelica.

Activity 2.2 Design of district energy systems, validated and demonstrated the tools from Subtask 1, applied to district energy systems and smart grid integration at the scale of the district energy system. Figure 6 shows a net zero energy neighbourhood. By coupling models of buildings, HVAC, electrical systems and controls, it was possible to assess the effect of building load onto the electrical grid and assess the efficacy of control measures.

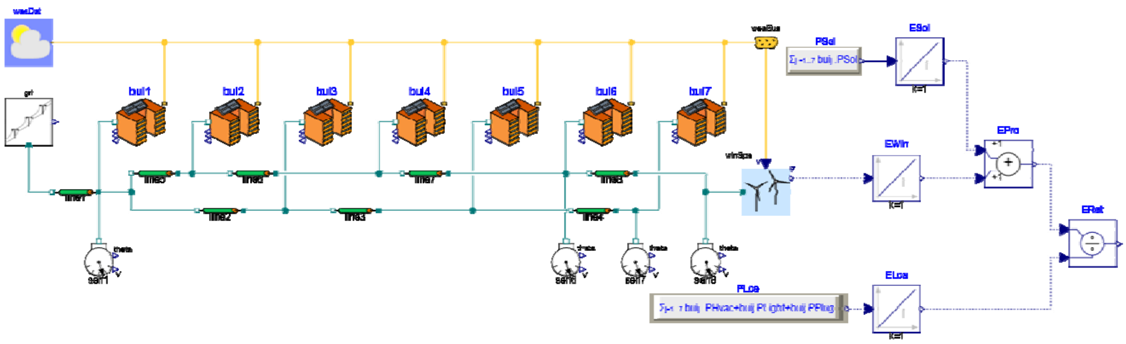

Figure 5 Neighborhood model with renewable energy sources

In addition, this activity identified the need for a testing framework for district energy simulation models: a DESTEST. This DESTEST aims at providing the structure for a common reference framework for testing models in a district energy simulation context, just like the BESTEST does for building simulation models. It also aims to become a benchmark for academic exercises for technological solutions, modelling or method assessment.

Activity 2.3 Model use during operation, used control models from Activity 1.1 and FMI export programs from Activity 1.2 during the operation of building energy systems, and during hardware-in-the-loop experimentation.
In particular, this activity provides insights into using Modelica models to solve real-world problems in real-time. Three applications are presented: Model predictive control (MPC); Fault detection and diagnosis (FDD) and Hardware-in-the-loop (HIL)

Subtask 3 – Dissemination

Subtask 3 focused on the dissemination of the results through special sessions at scientific conferences and through workshops that trained users in the technology developed in Annex 60. Beside the final report, Annex 60 published 12 journal articles, 38 conference papers and a Modelica library, which are all accessible at http://www.iea-annex60.org/pubs.html.

Several special scientific tracks at national and international conferences were organized to disseminate and promote results of the entire project. In order to represent the Annex in a consistent manner, a common text for the acknowledgement section of papers was formulated and distributed to all participants. The Annex 60 project gained a high international visibility through, among others, the following outreach activities:

- multiple announcements in the Newsletters of the International Building Performance Simulation Association (IBPSA),
- announcements in the Newsletter of its US-Affiliate IBPSA-USA,
- announcements in the Newsletter of the Modelica Association,
- presentation at the SimBuild 2012 conference in Madison, WI, USA,
- presentation of the Annex at the International Symposium “EnTool 2013 Symposium, Workshop & Summer School” in Dresden, Germany,
- presentation at the Modelica North-America User Meeting in Ann Arbor, Michigan, in May 2013,
- presentation at the IBPSA-USA meeting in Dallas, TX, in January 2013,
- presentation at a special conference track at the international Building Simulation conference in August 2013 in France,
- implementation of a special conference track at the BauSIM 2014 conference in Aachen, Germany,
- receiving the Best Paper Award for an Annex 60 paper out of 100 presentations at BauSIM 2014,
- implementation of a special conference track at the ASHRAE/IBPSA-USA Building Simulation Conference in 2014,
- presentations at the SIAM Annual Meeting in the USA in 2014,

- organization of special tracks at the Building Simulation 2015 conference in Hyderabad, India, where 28 joint papers were presented from the Annex 60 framework,
- presentations at a public workshop sponsored by the Netherlands and Flanders chapter of the IBPSA,
- presentations in 2016 at a public Annex 60 workshop with hands-on training by IBPSA-France,
- presentations at the Clima 2016 conference in Aalborg, Denmark,
- presentations at the ASHRAE and IBPSA-USA SimBuild 2016 conference in Salt Lake City, Utah, USA,
- presentations within a special track at the BauSIM 2016 conference in Dresden, Germany,
- invited presentation about Annex 60 and IBPSA Project 1 at the IBPSA-England BSO 2016 conference in Newcastle, England,
- presentation at the Modelica North America Users' Group meeting in Troy, Michigan in 2016,
- invited presentation at the international conference of the European Energy Research Alliance (EERA) in 2016,
- presentations at the Modelica conference in Prague in 2017, and
- presentation of the Annex 60 / IBPSA Project 1 continuation framework at the Building Simulation 2017 conference in San Francisco, USA.

Furthermore, progress of the Annex 60 framework was disseminated in a number of issues of the IEA EBC News.
The public Annex 60 web site is accessible at http://www.iea-annex60.org. This page also host papers that resulted from the Annex 60 collaboration, lists participants and their respective contact information.

1.6 Utilization of project results

As previously mentioned, the Annex60 library, which is one of the main outcomes of the project, is a free library. Therefore, it can be used not only by participants of the Annex, but also by others. The target audience of Annex 60 is the building energy research community, design firms and energy service companies, equipment and tool manufacturers, as well as students in building energy-related sciences.

Compared to conventional building simulation programs, the end-product provides the means to reduce energy consumption and peak power demand through:

- Rapid prototyping of new equipment, systems and controls that accelerates time-to-market for innovative low energy systems. Engineers in leading edge design firms are not restricted to design, test the performance, and size systems for which implementations in conventional building simulation programs already exist. Rather, they themselves can add models of innovative technologies, which may not yet have deep enough market penetration to have implementations in conventional building simulation programs.

- Standardized APIs that contribute to simulator interoperability, which allow designers to link different simulators for run-time data exchange in order to conduct integrated analysis of buildings in which control loops are closed across domains that are simulated by different tools.

- BIM to Modelica translators that provide a means to specify in a BIM not only the envelope and HVAC components, but also their control sequences. During design, this allows improving the effectiveness of controls to reduce energy and peak demand using a BIM-based process. During commissioning, the actual implemented control sequences can be verified versus an executable representation of the design intent, as stored in the BIM. Furthermore, building performance models can be updated more efficiently in terms of following model changes within an integrated planning process.

- The quantification of risk, the co-design of HVAC and control sequences and sizing that takes into account thermal storage (where equipment size is the solution to an optimal control problem) allows proper sizing of systems, thereby avoiding inefficient operation due to operating equipment at low part-load efficiencies.

- Peak load reduction and load shifting at the community level that allows reducing the need for electrical reserve capacity generators, which typically have high CO_2 emissions and large capital costs.

- The use of models to augment monitoring, control and fault detection and diagnostics methods. This promises to detect a degradation of equipment efficiency over time because measured performance can be compared to expected performance at the current operating conditions. Furthermore, use of models during operation allows operational sequences to be optimized in real-time to reduce energy or cost, subject to dynamic pricing.

1.7 Project conclusion and perspective

The technology development in Annex 60 was organized around three standards:

- IFC for data modelling,
- Modelica for multi-domain, multi-physics modeling, and
- FMI for run-time interoperability of simulators.

Basing the work on these standards was critically important to enable joint technology development among multiple participants, many of whom brought into Annex 60 their existing code, further developed it within the project, and then integrated it back into their tools.

A prime example of technology developed around these standards is the Modelica Annex60 library developed in Activity 1.1. In this work, multiple institutes started a collaborative development of a free, open-source Modelica library for building and district energy systems. This work harmonized the previously fragmented and duplicative development of libraries, and resulted in a jointly developed library that is now used by four major Modelica libraries for building systems.
A second example of technology developed using the previously mentioned standards is the development of building and district energy simulation tools based on the FMI standard. A key advantage of using the FMI interface is that it decouples

the model authoring from the simulation run-time environment, allowing quite different approaches to be used to integrate the models in time. Over the course of the project, different FMI simulators not only emerged from within Annex 60, but also from within the significantly larger FMI community
A third example of technology development using these open standards is that which was done to support processes that transform digital planning and design to simulation. In Annex 60, a mechanism was developed to transform a digital model of a building and its energy systems to Modelica code, which can then be readily used for advanced building performance simulation. Annex 60 thoroughly addressed the prevailing tedious, cumbersome and error-prone process of manual data conversion and model generation by providing a methodology and software framework for automatically, or at least semi-automatically, transforming a digital model into an object-oriented acausal model.

Subtask 2 demonstrated how these technologies can be used for the design and operation of building and district energy systems. In many of these applications, models from Activity 1.1 were combined with FMI-tools from Activity 1.2 and workflow automation scripts from Activity 1.4, and with open-source and commercial software that has been developed outside of Annex 60, to solve problems related to the design and operation of building and district energy systems. The case studies showed that very low energy systems and increased grid integration imposes structural changes to building and community energy modeling and simulation tools and processes.

Although the Annex has delivered a solid basis of tools and demonstrated their application, tool development is a continuous effort. It continuously needs to provide support, respond to new system technologies and apply advances in computer science and applied mathematics. Upcoming research and development issues that remain to be solved after completion of the Annex will therefore be coordinated under the umbrella of the network of the International Building Performance Simulation Association (IBPSA) as a living and supporting dissemination framework.

Annex

Relevant links:

Official website of Annex 60: http://www.iea-annex60.org
Publications: http://www.iea-annex60.org/pubs.html