GENERATING REDUCED MODAL MODELS OF BUILDINGS FOR ALLAN.™SIMULATION

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ABSTRACT

The Research and Development Division at Gaz de France assesses and improves building heating and cooling equipment by both experimental and modelling/simulation approaches. In this context, the R&D Division uses two tools to model the thermal dynamic behaviour of buildings : the ALLANTM. Simulation modeller connected to the NEPTUNIX solver, and the CSTBat software.

In 1993, GDF chose the CSTBat building description file format for both tools. The Groupe Informatique et Systèmes Energétiques (GISE), which is working on modal techniques applied to the thermal dynamic modelling of buildings, developed with GDF a package to generate building models automatically in the ALLANTM.SiMUlation environment from the CSTBat description and provide modal reduction techniques.

We will show here how this has been done using some advantages offered by the SYMBOL project and gathered in the m2m package to generate the reduced modal model.'GISE wrote the m2m2allan tool to put it in a form suitable for ALLANTM.Simulation.

GISE and Gaz de France validated the process jointly in three steps : they carried out operational validation first, then qualitative validation and last experimental validation.

In this paper, we will focus on the tasks performed in order to link the tools, and on the translator. Some background information on the modal technique and its reduction capabilities will be supplied. The function and advantages of the m2m package are stressed. Examples will be given to demonstra , te the performance of the m2m package in the ALLANTM.Simulation environment through its experimental validation, and the improvement 'obtained in terms of variable and equation numbers by modal reduction. We will then show how the package is currently being used in the Research and Development Division in several studies dealing with heating and refrigerating plants in buildings.

INTRODUCTION

The Gaz de France Research and Development Division uses two tools to model and simulate the dynamic thermal behaviour of buildings and equipement : the ALLAN™.Simulation modeller connected to the NEPTUNIX solver (noted ALLAN in the following), and the CSTBat software. In 1993, GDF decided to unify the building description in both tools.

The CSTBat building description file was chosen for both tools: ALLAN and CSTBat. Interested in model reduction with modal techniques (Carter 1979; Shih et al. 1983; Sicard et al. 1985; Lefebvre et al. 1990; Lefebvre et al. 1993), GDF asked the Groupe Informatique et Systèmes Energétiques (GISE) to develop a package which would automatically generate building models in the ALLAN environment from the CSTBat description and provide modal reduction techniques.

CONTEXT AND PROBLEM TO BE SOLVED

CSTBat

CSTBat is based on TRNSYS. TRNSYS was developed at the Solar Energy Laboratory of the University of Wisconsin in Madison and still sold in 1975 (Klein 88). CSTBat was developed by the French Scientific and Technical Center for the Building Industry CSTB (Laret 88). The difference is that CSTBat includes an interface to input the construction characteristics of the complete energy system under study, a library of advanced component models and numerical technique implementations.

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In particular, the interface works from a textual description of the building in order to generate different models for the TRNSYS simulation. There are four different levels of building models (Laret 91).

ALLAN

ALLAN is a program designed at the GAZ DE FRANCE Research and Development Division and developed with the aid of CISI. It is a general software package for the description and simulation of dynamic systems (Favret 88, Jeandel 93).

ALLAN.Simulation is a pre- and post- processor. It is not a simulation program: simulation is provided by the choice of a solver. It is used at GAZ DE FRANCE and in other companies to describe and manage models for the NEPTUNIX simulation program.

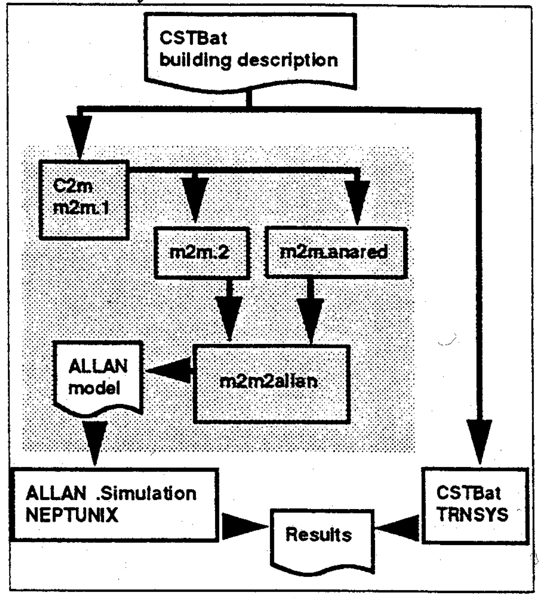
A software comparison and today's strategy
Both software packages (CSTBat and ALLAN) have shown their advantages and disadvantages. CSTBat offers high-quality models and a very convenient text description format for buildings and equipment. FORTRAN programming is required to add a new model, especially if the user wants to run the interface program. ALLAN does not require code programming for new models. It is general and open to new models; the drawback is that it does not have any convenient utility program for modelling buildings.

GDF decided to support ALLAN and to make ALLAN as convenient to use as CSTBat for building descriptions.

THE m2m/SYMBOL SOLUTION

The idea was to allow ALLAN to use the textual building description originally developed for CSTBat. For a long time now, CSTBat has already been using the same output format as ALLAN to write the simulation results.

GDF wanted to be able to choose the modal reduction technique to generate a model and furthermore to have mathematical criteria to do so and to evaluate the resulting model. An adaptation of several modules of the m2m/SYMBOL package (called m2m here after) and the development of some tools suiting the specific needs of GDF was made by GISE. Starting from a building description it is possible to generate the algebraic-differential equations for ALLAN in three different ways : without any reduction with `m2m.1`, with a simple mode truncation reduction `m2m.2` or by means of a more sophisticated modal reduction with `m2m.anared`. Two specific tools were written. `c2m` translates the CSTBat description into a suitable m2m one, before any modal calculation. `m2m2allan` translates the m2m resulting model in the ALLAN syntax.



The reduced thermal modal modelling of buildings : the m2m tools
GISE develops methods and software tools enabling the description, analysis, and simulation of complex thermal systems, some of them by taking advantage of the reduction possibilities of the modal techniques. These tools have been developed until now in the SYMBOL project, one of the main result of which is the m2m package. This package can be used to model the dynamic behaviour of thermal systems such as buildings.

Principals of the modal method
The main idea of the modal method is to perform an expansion of the temperature field on the basis of eigenvectors, and to reduce the model by taking off the less significant terms of the (theoretically infinite) series. Different ways can be used to determine the eigenelements (eigenvectors and eigenvalues). The most usual one is to diagonalize the following ordinary differential system:

$$\mathbf{C}\frac{dT}{dt} = \mathbf{A}\,T + \mathbf{E}U$$
$$Y = \mathbf{J}\,T + \mathbf{G}U$$

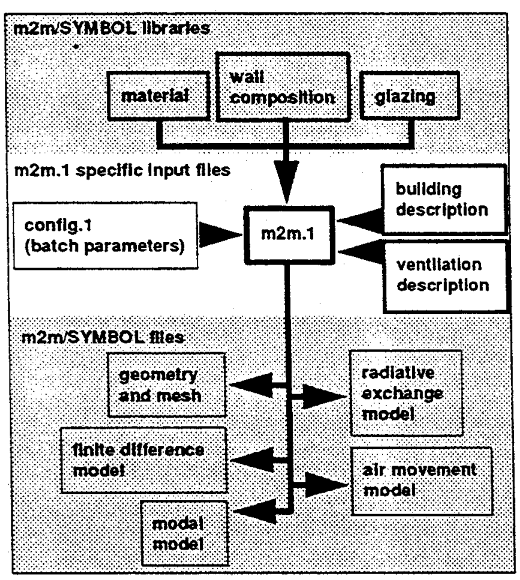
which can be obtained by applying a finite difference discretization of the heat transfer operator on a mesh. $\mathbf{C}$ is the diagonal matrix of the capacities of the nodes, $\mathbf{A}$ is the heat exchange matrix between these nodes, $\mathbf{E}$ is the excitation matrix which links the input U (outdoor temperature, heat flux dissipated in each zone, incident solar fluxes, etc.), to the heat balance of each node. Y contains some particularly interesting observed variables (indoor air temperatures, resulting temperatures, etc.) which are expressed as linear combinations of temperatures and inputs. The size of the model depends on the number of inputs and outputs, but also on the number of nodes. By diagonalizing $\mathbf{C}^{-1}\mathbf{A}$ and performing some convenient transformations, the following formally equivalent system can be deduced from the previous one:

$$\frac{dX}{dt} = \mathbf{F}\,X + \mathbf{B}\frac{dU}{dt}$$
$$Y = \mathbf{H}\,X + \mathbf{S}\,U$$
$$T = \mathbf{P}\,X + \mathbf{S}_T\,U$$

in which $\mathbf{F}$ is a diagonal matrix containing the eigenvalues of the system, and $\mathbf{P}$ the corresponding eigenvectors. $\mathbf{F}$ being a diagonal matrix, the modal state variables X evoluate in a decoupled manner. The time integration of this system is easier than the previous one, needs less calculations, and provides faster simulation. The initial calculation of the modal model by diagonalization is more CPU-expensive than just the matrix inversion required when simulating with the first model, but can be compensated for by the time gain obtained by reducing the order of the model. The modal reduction will consist of taking off some vectors from the initial model and then reducing the number of rows in matrix $\mathbf{B}$, the number of columns in matrices $\mathbf{F}$, $\mathbf{H}$ and $\mathbf{P}$. As the asymptotic steady state value of each X is zero, the truncation reduction is achieved by taking off the corresponding rows and columns. This is the purpose of **m2m.2**. But the residual dynamic error can be compensated for by corrections resulting from some convenient combinations of the eliminated eigenvectors. This is how **m2m.anared** proceeds. We shall provide below more details on these concepts, illustrating them with outputs calculated on a simple example.

m2m.1

m2m.1 processes a building description and builds a modal model. It is the only building specific module.



All files are written with a common SYMBOL syntax which allows easy communication between the different modules of the environment. The "batch parameters" file, `config.1`, contains the names of the input and output files, but also some flags determining the particular behaviour of the **m2m.1** executable module. In this way, it is possible to specify the desired type of wanted inputs and outputs, and to choose between different modelling assumptions. When the simplest modelling assumption is chosen, the model created includes all heat transfers phenomena; however, due to the assumptions needed to apply the modal method, the ventilation rates must be constant and symmetrical, and the radiative exchange must be expressed in a linear form. If these assumptions are not valid, the corresponding phenomena (ventilation or radiative exchanges) can be removed from the main model and included in a different one. The solver must then handle the different coupled models during the simulation. Ventilation exchanges can be handled inside the model if they are symmetrical and constant, outside of the main model if not. Radiative exchanges are taken into account inside the main model through global heat exchange coefficients or in an auxiliary model, by a radiosity method. In order to give the user a reference model, the finite difference model can be written in a separate file. As the mesh is automatically specified by **m2m.1** (but it can optionally be imposed by the user), the geometry file indicates the chosen number and characteristics (location and size) of the nodes.

m2m.2

This module takes a modal m2m file as input, and produces another modal m2m file as output. It is not specific to building energy studies. Both describe the same system, and have the same inputs and outputs variables. **m2m.2** must know the name of both files, and the desired size of the output model. **m2m.2** automatically performs a reduction of the input model at the desired order, following a simple truncation algorithm explained bellow.

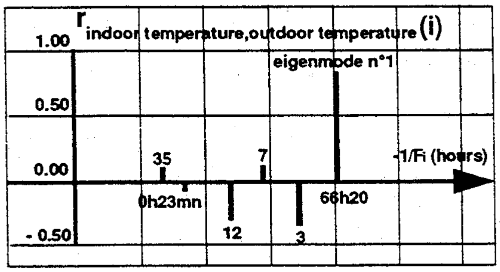
The contribution of each i eigenmode to the response of output q to input p can be analysed by looking at the following quantities:

$$r_{qp}(i) = -\frac{\mathbf{H}_{qi}\,\mathbf{B}_{ip}}{\mathbf{S}_{qp}}$$

which are the factors that appear in the expression of a step response:

$$Y_{qp}(t) = \mathbf{S}_{qp}\,(1 - \sum_{i=1}^{N} r_{qp}(i)\,e^{\mathbf{F}_i t})\,\overline{U}_p(t > 0)$$

As all the dynamic information is included in a step response, it is valid, in a first approximation, to quantify the eigenmode contribution by the $r_{qp}(i)$ values. This set of values, associated with the corresponding eigenvalues, is called the response spectrum of output q to input p, and can be represented by the following graph:



In general, only some eigenmodes have a non negligible contribution; they are called "dominant" modes. This is the main characteristic of the modal representation, the one that validates the reduction power of such models.

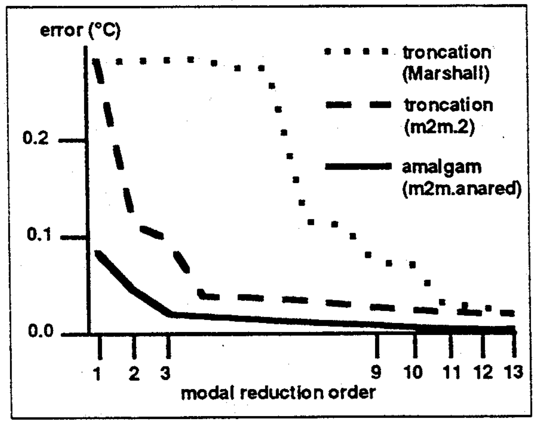
But a response spectrum, and then the mode dominance, depends on a particular input p and a particular output q. **m2m.2** mixes all the possible response spectra by allocating the largest absolute value $|r_{qp}(i)|$ among all the possible response spectra $p \rightarrow q$ to each mode i, sorts the modes versus the decreasing absolute values, and keeps only the first R ones, R being the desired reduced model order.

m2m.anared

Like **m2m.2**, **m2m.anared** is an m2m modal reducer tool. The amalgam is a very powerful method for reducing modal models. We will indicate only its principle, as more details are published in (Oulefki 1993). A first stage consists in ordering the modes versus the reduction error they would generate if they were taken off the model. The error is measured as the time-space integrated error of the field temperature in the system.

At a second stage, the modes eliminated by the reduction process are agregated to the remaining ones, using a deterministic algorithm in which each non dominant mode is associated to a dominant mode, choosing it in order to induce the smallest error.

This method is much more efficient than the previous one, and despite its apparent complexity, is not very time consuming. The gain of accuracy is fairly significant, and it is possible to set the reducing order, or the required accuracy (in term of maximum allowed error) as a reducing objective.

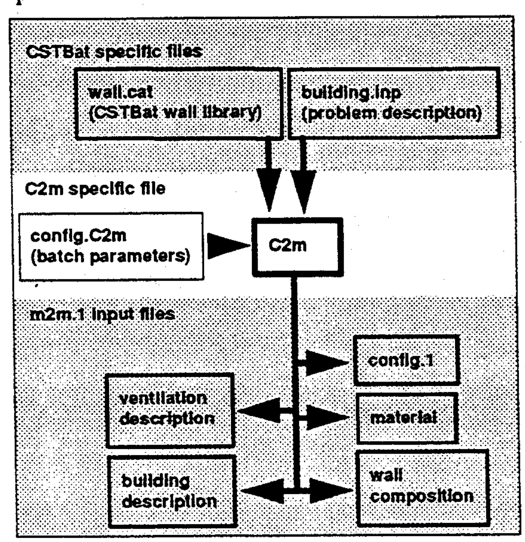


Integration of the m2m tools in the ALLAN environment

To be able to use the modal facilities in order to model buildings in the ALLAN environment and to use a CSTBat description, it was necessary to write a CSTBat-m2m translator (we called it **c2m**), and an m2m-ALLAN translator (called **m2m2allan**).

Chaining CSTbat with m2m

A specific tool, **c2m**, was written. **c2m** reads the CSTBat files, takes the needed information, and builds an internal structure equivalent to the one used in **m2m.1**. The same basic modules and structures are used, and the "write" facilities of m2m are used to produce the files required by **m2m.1** as input.



Some differences between the structures and the modelling assumptions required adaptation of the structure of **m2m.1**. For example, CSTBat models windows as transparent walls, while **m2m.1** has a specific window structure; CSTBat describes the ventilation network as closed loops, while **m2m.1** accepts a graph of zone-zone edges. The boundary conditions are set in CSTBat by an "environment" entity which are special air volumes with imposed temperature, while **m2m.1** simply allows the temperature of any regular zone to be imposed.

m2m.1 was then modified by increasing its capabilities and its generality. For example, it is now possible to describe a window as a transparent capacitive wall, or as an **m2m.1** window, which is taken into account internally as a non capacitive transparent wall. These modifications were easy to make, due to the modularity and flexibility of the m2m code and structure.

Chaining m2m with ALLAN

As seen above, m2m codes generate, after reduction, an m2m file, which contains information on the size and dimensions of the linear reduced system, as well as the values of the coefficients of each matrix. The task of translating that m2m file into working ALLAN code is entrusted to the **m2m2allan** translator.

For ease of programming, the language used for coding **m2m2allan** was **awk**, one of the small languages of UNIX™. **awk** is neither quick nor big, but was good enough for the task, and also makes it fairly easy modification of the translator. **awk** works in essence as a line filter that recognizes regular UNIX expressions, tokenizes the line containing them (that is, separates the "words" of the line), and then performs user specified actions on the tokenized line, using the **awk** action language, which is a subset of the C programming language.

As the m2m syntax is very simple, **awk** parsing was enough. For more complicated grammars, resorting to more advanced parser generators like Lex and Yacc would have been necessary.

The implementation of the translator was straightforward: each line of the m2m specification was analyzed. Upon encountering keywords limiting m2m file sections, the translator was internally put into a specific mode and performed the relevant actions. Its internal structures were essentially the m2m reduced matrices, which were then translated into the symbolic representation of the associated linear equation system, fit for ALLAN processing. Additional items such as declarations or initialization routines for certain parameters were created, based on the inner storage by **awk** of variables names and the like.

Several options are available for **m2m2allan**, with respect to the m2m matrix format and the kind of output format. Provisions were also taken in order to accommodate internal ALLAN limitations on the size of equations (number of independant variables). For example, if

$$\frac{dX_i}{dt} = \sum_{i=1}^{25} a_{ij} X_j$$

is too big for ALLAN, the equation can be cut in two or more parts, as in:

$$\frac{dX_i}{dt} = Z_u + Z_{u+1}$$

$$Z_u = \sum_{i=1}^{12} a_{ij} X_j$$

$$Z_u = \sum_{i=13}^{25} a_{ij} X_j$$

Thus, intermediate variables were introduced, with two consequences: a higher complexity of the **m2m2allan** code, and also the introduction of purely algebraic equations in the system, which led later, in some cases, to numerical problems for NEPTUNIX, the internal ALLAN solver.

The use of **m2m2allan** is trivial. The input m2m file name is specified, and the appropriate ALLAN file is then created.

VALIDATION

CSTBat has already been validated with the aim of verifying the quality of the results obtained, within the limits of its modelling assumptions (Paléro I. 1990). The objective now is to offer users of ALLAN the advantages already offered by the CSTBat description file. We decided to validate the required chain using the methodology defined to validate CSTBat. The same test cases were used whenever possible.

We therefore validated the CSTBat-m2m-ALLAN chain. The process was broken down into two stages: qualitative validation and experimental validation.

Qualitative validation seeks to ensure that the models generated behave as expected when subject to standard forms of stress. The validation process used models generated from CSTBat description files processed successively by the programs **C2m**, **m2m.1** and **m2m2allan**. Validation verified the coherence of the translated CSTBat description files, the relevance of the **m2m.1** modelling hypothesis and the application of these assumptions by the model described in ALLAN. Two types of building were modelled: one single-area and one dual-area, with or without ventilation. Ventilation was processed by coupling the model created by the chain with ALLAN models representing the exchanges induced by ventilation. Three types of protocols were applied to these models: outside temperature step, heating power step, variations in the value of the incident solar flux.

Validation studies showed the performance of the gateway to be satisfactory, in compliance with the modelling assumptions of **m2m.1**. The deviations observed with CSTBat are caused by different modelling assumptions: the solar flux is injected directly into the air node in **m2m.1**, distributed between the air node and the sunny surfaces for CSTBat; the heating power injected by underfloor heating or by a radiator is distributed differently; the models of dry bulb temperature are slightly different.

Empirical validation seeks to verify the quality of a model by comparing the results of simulations with the same values observed in test cases. We used a model generated by a CSTBat description file and processed successively by `c2m`, `m2m.1`, `m2m.anared` and `m2m2allan`. The system modelled is a two-room flat in the Gaz de France experimental building, in which a measurement campaign was performed in January 1993. This is the case used to validate CSTBat. Unlike the CSTBat model, the model generated by the gateway only describes the behaviour of the building, without modelling the network or heaters. Model inputs are temperature, power step and the density of the incident solar flux on each facade. These two last non-measured values were therefore calculated by CSTBat and added as input to the ALLAN model. Last, the building model created by the gateway was coupled with ALLAN models representing the exchanges set up by the ventilation network. Moreover, the 16-zone model was reduced from order 194 to order 10 by the modal amalgam software program, `m2m.anared`.

Certain minor flaws were observed, primarily due to the modelling assuptions (injection of heating power to air nodes) and the quality of the inputs calculated.

Experimental validation nevertheless showed the behaviour of the model generated by the gateway to be consistent. It also showed that the gateway makes it possible to process complex building components through the application of modal reduction.

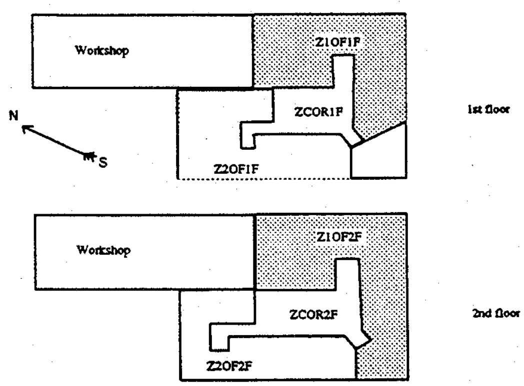
The gateway was thus functionally validated through a qualitative study of the models generated and a comparison of results with experimental data.

EXAMPLE

The gateway has already been used in a number of studies at the Gaz de France R&D Division. Modelling engineers can now give a simple description of a building, generate the corresponding ALLAN model by means of the gateway and couple it to other ALLAN models.

This was the case of a study on a natural gas fired air-conditioning system, which sought to optimize the primary hydraulic network and to evaluate the installation operating costs. A model of a building has been prepared and coupled with models for the production and distribution of hot and chilled water, the production and distribution of processed and cool air and the different control units.

The building modelled is a commercial one, located near Toulouse, in west southern France. The building has an air-conditioned area of 485m² on two floors. It has 25 offices and is adjacent to a 300m² workshop that is also part of the system modelled. For the CSTBat description file, we decided to split the building into eight areas. This breakdown was performed on the basis of criteria of functionality, position of the ventilation outlets and orientation: two office areas and one corridor area on each level, one area for the false ceiling between the ground floor and the first floor and one area for the workshop. The lightweight walls between the offices have low thermal inertia and were not addressed. The CSTBat description file was successively processed by the `c2m` and `m2m.1` programs.



The model was originally of order 307 in modal formalism, but was reduced to an order of 10 with `m2m.anared` and turned into an ALLAN model with `m2m2allan`. It was then associated with the ventilation models, and coupled to the air-conditioning and control systems within a reasonably short period of time. Before this, we would have been forced to use a model that was too detailed for the objectives of the study. The use of the software chain in the ALLAN design environment therefore saves time and preserves accuracy.

PROSPECTS

With a view to further development of the gateway in the future, a link should be set up between m2m and ULM (A. Jeandel *et al.* 1995). This software-independent modelling language notably makes it possible to describe models made up of several sub-models on a hierarchized basis.

We already have a ULM-ALLAN translator. As a result, the new software chain will make it possible to generate a compound model in ALLAN format from the textual description of a building in CSTBat format. Each sub-model would correspond to a zone. The zone models would be smaller and easier to handle. We could then process each zone model independently using `m2m.1`, `m2m.anared`, and then handle the coupling between the zone models during the simulation with ALLAN. This would enlarge the applicability domain of this software package, allowing to use it to model variable air flows, for example.

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