Simulation of Fire Propagation in Cable Tray Installations for Particle Accelerator Facility Tunnels

Tristan Hehnen[1,2], Lukas Arnold[3], Patrick van Hees[4] & Saverio La Mendola[2]

[1] Bergische Universität Wuppertal, Germany
[2] European Organization for Nuclear Research CERN, Geneva, Switzerland
[3] Institute for Advanced Simulation, Forschungszentrum Jülich, Germany
[4] Lund University, Lund, Sweden

ABSTRACT
In this paper, it is demonstrated that the simulation of fire propagation in cable tray installations, with the Fire Dynamics Simulator (FDS), version 6.3.2, can be achieved. A material parameter set allowing to estimate the fire spread, depending on environmental conditions close to the fire seat, was generated. The parameters are determined by utilisation of an evolutionary algorithm, in an inverse modelling framework, based on experimental data from Cone Calorimeter tests. As a further step, the performance of the parameter set is compared between the FDS versions 6.3.2 and 6.5.3.
The foundation of this work are experimental results of the CHRISTIFIRE campaign. The inverse modelling approach is inspired by and based on Anna Matala's and Chris Lautenberger's work.
A material parameter set generated by the evolutionary algorithm is then used in a real scale cable tray fire simulation to predict the fire propagation. The total heat release rate (HRR) of the cable tray simulation and the respective experiment are compared and are in good agreement. The major features in the HRR plot of the experimental data are visible in the simulation results, but slightly shifted in time. Thus, predicting the fire propagation in a simulation, based on data of small-scale experiments, seems possible with FDS.
However, the parameters used in this work are model specific and very sensitive to changes in the model, like grid resolution and FDS version.

KEYWORD: FDS, pyrolysis, CHRISTIFIRE, cone calorimeter, cable tray fire, inverse modelling, evolutionary algorithm, genetic algorithm, SCE-UA, particle accelerator,

INTRODUCTION

The European Organization for Nuclear Research (CERN) is one of the largest particle research laboratories in the world, situated north of Geneva in Switzerland and France. The Organisation's facilities are very divers and encompass a variety of surface buildings, ranging from office buildings, restaurants and hotels to computing centres, large storage facilities, workshops and experimental halls. Furthermore, extensive underground facilities house particle accelerators, which are connected via transfer tunnels between one another, and are directly connected to multi-storey experimental caverns. Combined they have a length of about 76 km [1]. The so-called accelerator chain (*Figure 1*) starts from a linear accelerator (LINAC 2) where protons are injected into the chain. They are accelerated close to the speed of light, before they are used in various experiments. During this process, the protons travel through different accelerators: the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) into the Large Hadron Collider (LHC). The accelerators LINAC 2, PSB and PS are housed in surface buildings. The facilities of SPS and LHC are deeper underground between 30 to 150 m. Access is provided via vertical shafts, some of which contain elevators and staircases, whilst others are clear of obstructions to allow for equipment and material transport, using cranes. The tunnel cross section diameters are between 4.5 m to 6.2 m. This allows for the movement of material and personnel. Distances between the access shafts range from 150 m for the PS up to about 3 km for the LHC. Since the accelerators are ring-shaped, the accelerator

tunnels are also used as ventilation ducts. Parts of the facilities are relatively old. For example, the PS has been in operation for nearly six decades now. Furthermore, plans for new accelerators are studied. One of which is the Future Circular Collider (FCC) study to design requirements for the FCC. This accelerator is envisioned to be housed in an 80 km to 100 km long, ring-shaped tunnel, up to 400 m below the earth's surface, with a tunnel diameter of about 6.2 m and distances between the access shafts of about 10 km.
During operation of the accelerators, the tunnels and experimental caverns, as well as the equipment installed therein, are subjected to radiation. Over time, this leads to parts of the equipment becoming activated (radioactive). The radiation levels depend on the location along the accelerator, with the highest radiation levels occuring at the beam dumps, the experimental caverns and kicker magnets. Thus, design fires for particle accelerators need to be carefully evaluated, when radiological release in case of fire has to be estimated.

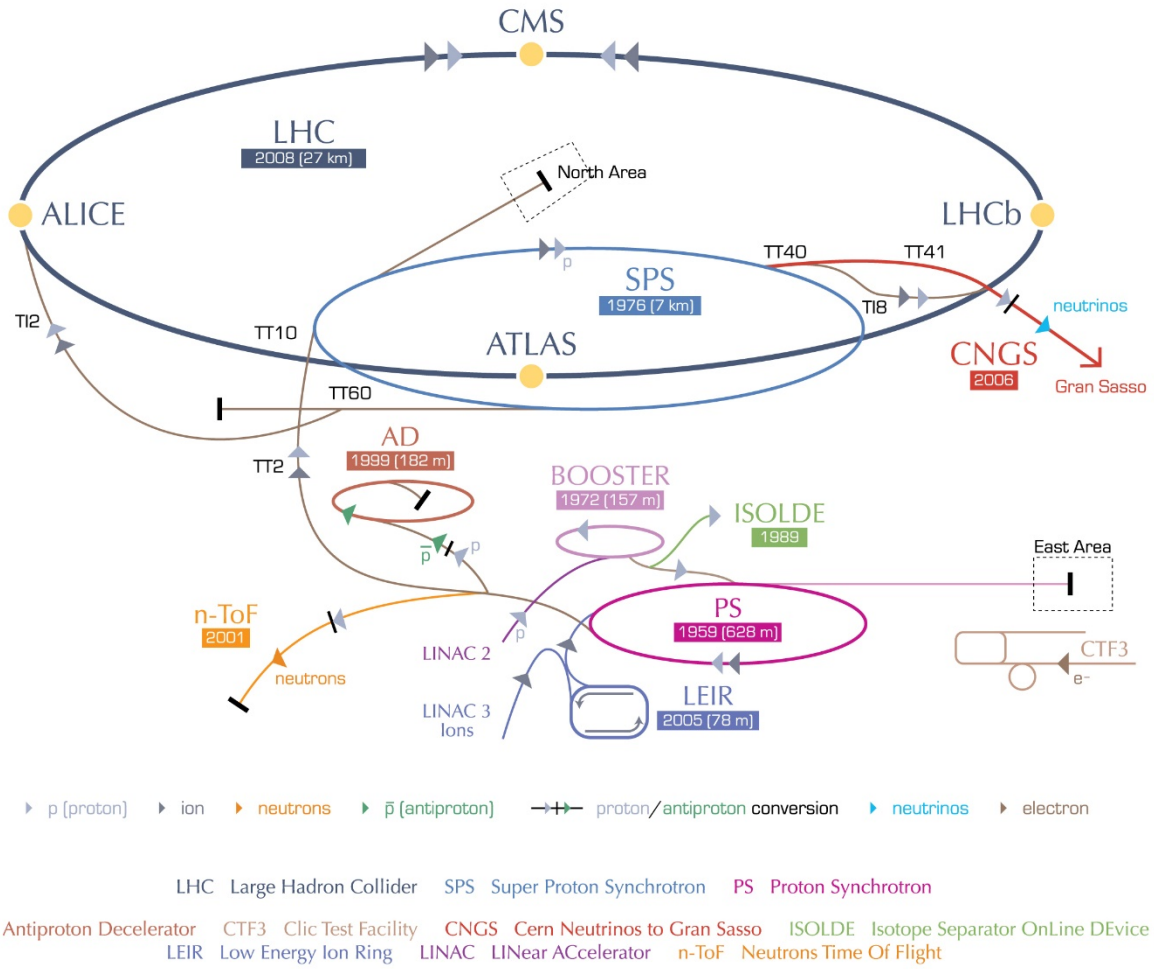


Figure 1: Schematic overview over the particle accelerator facilities at CERN [2].

The accelerator facilities contain a huge amount of electrical cables used for power supply, machine control and data transfer from the experiments to the data centres. Cables constitute one of the major hazards with respect to fire safety inside particle accelerator facilities. A cable fire can lead to the spread of smoke and heat within the facility, jeopardising people and equipment. Due to their unique layout and purpose, statistical data is scarce. Thus, other means to define the design fire need to be established.

Cables are a major fire load not only for CERN, but also in facilities like telecommunication data centres or nuclear power plants. In 2012, the United States Nuclear Regulatory Commission (U.S.NRC) published a report on an extensive cable fire test campaign which had been conducted in the previous years, titled "Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)" [3].

Given the rigid nature of design fires, different options are investigated to achieve a more detailed representation of fire and smoke spread simulation. Part of the ongoing research deals with the modelling of the pyrolysis reaction of a material, since it is an important factor when it comes to fire propagation. It determines how much combustible gas will be released based on the solid's temperature, thus determines the fire development. Often pyrolysis models are based on an Arrhenius equation because it allows to describe the results of small scale fire tests, which focus on pyrolysis like micro-combustion calorimetry (MCC), well. On an international level, different groups put effort into understanding pyrolysis and how to simulate this phenomenon properly. For example within the ongoing research, focus has been put on Latin-Hypercube sampling [4] [5], evolutionary algorithms [6] [7] or statistical methods like Bayesian updating [8]. It is of great interest for the fire safety community to have a reliable process which generates material parameter sets based on small scale experiments, that are able to replicate the fire behaviour within a simulation.

In this paper, it is demonstrated that the simulation of fire propagation in cable tray installations, with the Fire Dynamics Simulator (FDS), version 6.3.2 [9], can be achieved if appropriate input data can be obtained in combination with limited experimental testing work. A material parameter set was generated that allows to estimate the fire spread depending on the environmental conditions close to the fire seat. The parameters are determined by utilisation of an evolutionary algorithm, in an inverse modelling setup, based on experimental data from Cone Calorimeter tests.

MATERIALS AND METHODS

In the CHRISTIFIRE program, cable fire tests ranged from small-scale tests of the cable components with MCC, bench-scale tests with tube furnace and Cone Calorimeter to real-scale tests with cable tray arrangements in the open, in mock-up corridors and vertical shafts. This wide variety of tests makes the CHRISTIFIRE campaign a valuable source for the creation of design fires and the validation of simulation results. Out of the tested cables, cable #219 was chosen for this work, because it was one of the cables that was tested in a cable tray arrangement, where all trays were filled with this specific cable. Also, its behaviour during the Cone Calorimeter tests was very similar across all repetitions, while repeatability for other cables was not as good.

Focus was set on three different fire tests: MCC, Cone Calorimeter and cable tray installations in open space. The MCC tests have been performed by using a Pyrolysis Combustion Flow Calorimeter [10]. The MCC was used to determine reaction kinetics parameters of the pyrolysis reaction of the cable components jacket and insulator. Their pyrolysis has been modelled by utilising an Arrhenius equation during the CHRISTIFIRE campaign and the respective parameters are provided in the campaign's report. The results of the MCC tests and the Arrhenius model are reproduced in *Figure 4*. Furthermore, the heat release rates (HRR), production rates of residue and heat of combustion are provided in the report as well.

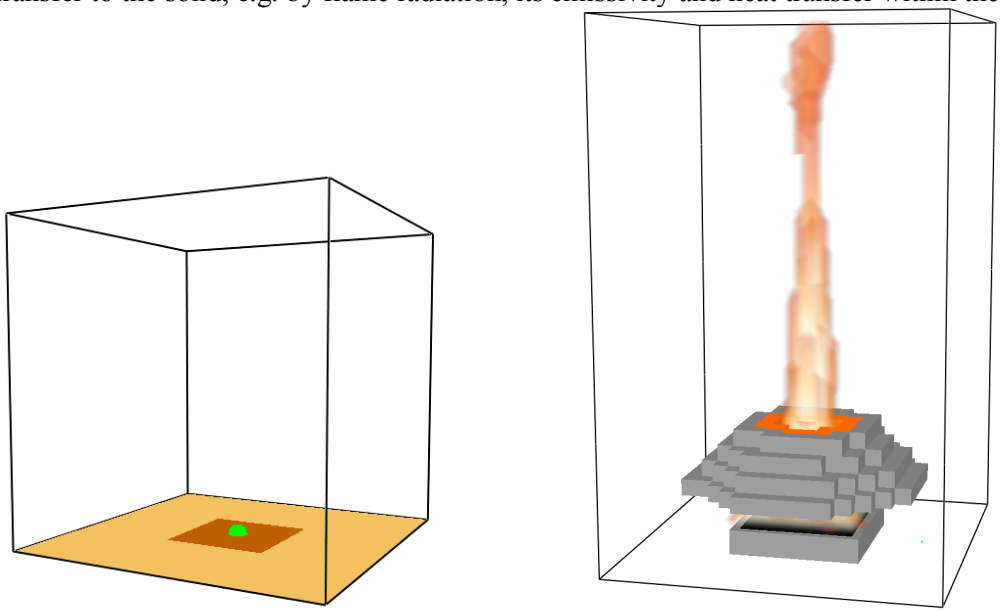
Cone Calorimeter tests were performed on cable pieces, which were neatly ordered in one layer in the sample holder. Incident heat fluxes were set to 25 kW/m², 50 kW/m² and 75 kW/m². Three repetitions were performed for each of the first two incident fluxes, one repetition for 75 kW/m². The results of the Cone Calorimeter tests are reproduced in *Figures 5 and 6*. Since the repeated tests for 25 kW/m² and 50 kW/m² yielded similar results, they are summarised by a grey area in the plots.

Cable tray installations (Multiple Tray Tests – MT) were tested in different sizes under a large hood, up to seven trays were stacked upon each other. The width of the trays was 0.45 m, vertical distance between the trays was 0.3 m while the tray length varied. Two different approaches were used to determine the total HRR, by oxygen consumption and mass loss. For the simulation of cable #219, focus was set on the HRR measurement based on oxygen consumption. The chosen test was MT-3, which consisted of three trays.

Within the CHRISTIFIRE framework, a simple fire propagation model for cable trays was developed, called FLASH-CAT (Flame Spread over Horizontal Cable Trays) [3]. It distinguishes between thermoset and thermoplastic cable insulation material, in terms of fire propagation. For CERN the FLASH-CAT approach has been adopted to create design fires to perform assessments of the smoke management within its facilities.

On the simulation side of things, the Fire Dynamics Simulator (FDS) [9] was used. FDS is a three-dimensional computational fluid dynamics software, which numerically solves a low mach number

specialisation of the Navier-Stokes equation. The computational domain needs to be divided into small rectangular cells creating a mesh. Within this mesh, the transport of fire-driven gas flow and heat transfer is then simulated.
In FDS, objects are defined by their geometry and the material properties. The geometry is built out of box-shaped obstructions (FDS: OBST) that influence the flow field. Surfaces (FDS: SURF) are then attached to the sides of the obstructions, which contain the respective material information (FDS: MATL). MATL describes the material properties like density, thermal conductivity or heat of combustion, while the SURF contains information of its application. It does not need to be homogeneous, but can consist of layers of different (homogeneous) materials.
FDS provides different ways to model fire propagation, e.g. when the surface temperature reaches a specified threshold, a prescribed mass flow is initiated. A more sophisticated method is based on an Arrhenius model for the pyrolysis reaction kinetics of a solid material [9]. Parameters for the Arrhenius model are the activation energy E, the pre-exponential factor A and the reaction order n. The same parameters as provided in the CHRISTIFIRE report. During the pyrolysis process, one or more new gaseous and solid species are generated and the original material is consumed. If a sufficient amount of combustible gas is generated, and combustion is possible, a flame can develop. The temperature of the material is used to control its degradation, which is in turn controlled by the energy transfer to the solid, e.g. by flame radiation, its emissivity and heat transfer within the solid.



(a) (b)

Figure 2: SmokeView visualisation of different simulation setups: Simple Cone with 10 cm cube-shaped cells (a), Coarse Cone with 7.5 mm cube-shaped cells (b).

Four different simulation setups for FDS were created to simulate the different fire tests: MCC, Simple Cone, Coarse Cone and MT-3.
The simulation setups of MCC and Simple Cone are basically the same, where no gas phase reactions are simulated and were based on suggestions in the FDS user's guide [9] and in the work of Anna Matala [6]. The focus was soley on the pyrolysis reactions, with the aim to reduce the demand for computational resources to a minimum.
The simulation setup of the MCC consists of four cells in each direction. The temperature of the whole domain was linearly increased over time to simulate the behaviour of the real MCC test.

The Simple Cone simulation setup (*Figure 2a*) was based on [6]. Its computational domain was divided into cube-shaped cells with an edge length of 10 cm and a total extension of 30 x 30 x 40 cm³. The sides and the top of the mesh were given an "open" boundary condition, while the bottom surface was closed. The layered SURF was attached to the bottom boundary of the central cell, to represent the cable sample. Due to the poor resolution in this setup, the incident heat flux to the cable sample was prescribed, using the FDS parameter EXTERNAL_FLUX on the SURF.

It was later found that suppressing the gas phase reactions (flame) was too much of a simplification. Mainly, because it neglected a significant amount of heat, radiated from the flame to the sample surface [11]. Attempts were made to prescribe an extra amount of heat flux and add it directly to the value for EXTERNAL_FLUX. The specific amount was determined by a simulation of higher fidelity (*Figure 2b*). However, it was realised that the external flux became a limiting factor during the inverse modelling process (IMP), which is covered later.
To assess the sensitivity of the material parameter sets of cable #219, in terms of mesh and flame resolution, a coarse replication of the Cone Calorimeter was created in FDS. The Coarse Cone was set up in a 7.5 mm cube-shaped mesh, where the radiative heat flux is generated by a hot, conical-shaped surface (*Figure 2b*). Within the Coarse Cone simulation setup, the parameter sets were subjected to heat fluxes as during the CHRISTIFIRE experiments (25 kW/m², 50 kW/m² and 75 kW/m²).

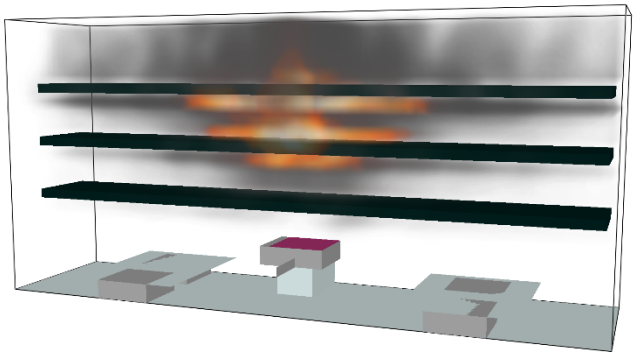


Figure 3: SmokeView visualisation of Multiple Tray Test 3 (MT-3) simulation setup (5 cm cubic cells).

Furthermore, a representation of Multiple Tray Test 3 (MT-3) from CHRISTIFIRE Phase 1 was created in FDS (*Figure 3*). The simulation setup of MT-3 was based on a mesh with 5 cm cube-shaped cells. Due to the resolution, the geometry of the tray racks themselves has been neglected. The cable layers in each tray were modelled as obstructions of 0.4 m width and a length of 3.1 m. The thickness of each cable layer was of one cell size (5 cm). This enables FDS to calculate the heat transfer in the solid while taking the temperature of the opposite surface into account, due to software limitations. However, this thickness is only of importance for the flow field. For the heat transfer in the cable material a thickness of about 1 cm was prescribed via the SURF, depending on the specific parameter set coming from the IMP. A vertical distance of 0.3 m was kept between the three trays, measured bottom to bottom. Some obstructions were put on the bottom of the simulation domain to mimic the supporting structure of the tray racks, which can be observed on the photographs in the CHRISTIFIRE report. A Propane gas burner, 0.3 m edge length, was located 0.2 m below the lowest tray and provided 40 kW for the first 600 s of the simulation.

It was briefly mentioned above, that the Simple Cone simulation setup was used with supressed gas phase reactions, which was later changed. The reason is, that the amount of combustible gas released determines how large the flames will be, which in turn determines the mass release, as well as the amount of radiation sent back to the sample surface [11]. Therefore, prescribed flame fluxes lead to inaccurate burning behaviour during the IMP. As proposed by Anna Matala [6], gas phase reactions were allowed again, even though the cell resolution in the simplified Cone Calorimeter simulation setup was very coarse (10 cm cube-shaped cells). With higher resolution, tall flames were observed, which are in line with observations of real Cone Calorimeter tests (*Figure 2b and Figure 4*). This behaviour could not be covered with the coarse grid, but it still allowed to cover parts of the flame's radiation influence. Methane was used as surrogate fuel for the combustion process.

Figure 4: Cone Calorimeter experiment.

Before the inverse modelling, attempts were made to use reaction kinetics parameters accompanied by the information on residue formation and heats of combustion provided in the CHRISTIFIRE report, directly for the materials in FDS. The remaining thermo-physical parameters were based on the example cases provided with FDS and literature values. However, performance was not satisfactory, except for the simulation of the micro-combustion calorimetry (MCC). Thus, focus was shifted to an inverse modelling approach.
Material and reaction kinetic parameters have been determined by utilising the global optimisation method SCE-UA (short for: shuffled complex evolution method developed at The University of Arizona) [12] in an inverse modelling approach. The IMP was controlled by a self-developed script, utilising the scripting language Python, version 2.7 and the Python package "Statistical Parameter Optimization Tool for Python" (SPOTPY) [13]. This script worked basically as the interface, handling communication between the SCE-UA and FDS.
First an input file for FDS is created and set up as a template. Markers in the template allow the input file to be parsed and the markers to be swapped to the specific parameter values. Another file contains the experimental results that are used as target information. A setup script provides input data for the optimisation process, as defined by SPOTPY. Each parameter was given a lower and an upper value, to limit the search space and to avoid to receive unrealistic values. However, the values are somewhat artificial. The limiting values are basically guess values, loosely based on literature values. For instance, the heat of combustion values got a range of ± 20% around the CHRISTIFIRE values, and were expanded when the algorithm got "stuck" at one of the limits during the search.

Table 1: Overview of which parameters were used during the IMP. The 'x' denotes individual parameters that the optimization algorithm had access to.

Parameter	Jacket reaction A	Jacket reaction B	Jacket residue	Insulator reaction A	Insulator reaction B	Insulator residue	Copper conductor
Density	Same for reaction A and B		x	Same for reaction A and B		x	
Emissivity	Same for reaction A and B		x	Same for reaction A and B		x	
Conductivity	Same for reaction A and B		x	Same for reaction A and B		x	
Specific heat	Same for reaction A and B		x	Same for reaction A and B		x	
A	x	x		x	x		
E	x	x		x	x		
n	x	x		x	x		
Heat of combustion	Same for reaction A and B			Same for reaction A and B			
Heat of reaction	Same for reaction A and B			Same for reaction A and B			
Layer thickness	Same for reaction A and B			Same for reaction A and B			x

Per generation the number of complexes has been the number of parameters n_{para} plus 1. Each complex contained two times the number of parameters n_{para} plus 1. Thus, the number of individuals (parameter sets) per generation n_{gen} can be described as:

$$n_{gen} = (n_{para} + 1) * (2 * n_{para} + 1)$$

Which is the default setup for SPOTPY. After the parameter sets have been created by SPOTPY, they were written into the FDS file, and the simulation was performed. From each simulation only the time and HRR data was kept, the rest was deleted to save hard drive space. The root mean squared error (RMSE), calculated between the experimental and the simulation results, was considered as the fitness value. Parameter sets which had RMSE values closest to zero were rated best. After all parameter sets of a generation had been assessed, they got ranked, shuffled and the new generation was generated.

The shuffeling is aimed to prevent the optimisation algorithm getting stuck at a local optimum instead of finding the global optimum of the search space. The process was terminated when either a specified number of simulations had been performed, about 100k, or the fitness value did not improve less then $1*10^{-6}$ % over the course of the previous 100 evolution loops (also SPOTPY default).

The SCE-UA was used on the Simple Cone simulation setup, with the experimental results from CHRISTIFIRE as target. Specifically, only one repetition of the 50 kW/m² Cone Calorimeter results was chosen as target for the IMP.
The cables were simplified as a SURF with three layers (jacket – insulator – jacket), to account for the assembled nature of electrical cables. By using the EXTERNAL_FLUX parameter, the conditions of Cone Calorimeter tests could be replicated easily. This approach was regarded to be sufficient for the demonstration purpose, thus reducing the computational costs of the IMP significantly.

In total 34 parameters were used for the optimisation algorithm to work on. Those are the thicknesses of the different layers, reaction kinetics parameters and thermo-physical parameters for each cable component, as well as thermo-physical parameters of the residues. In the beginning, the copper conductor was implemented as well, but only its layer thickness was accessible for the IMP. During every run of the IMP the thickness of this copper layer was reduced to its lower limit, thus it was removed completely. This behaviour is also in line with findings reported by Anna Matala [6]. An overview of the parameters used during the IMP is provided in Table 1.

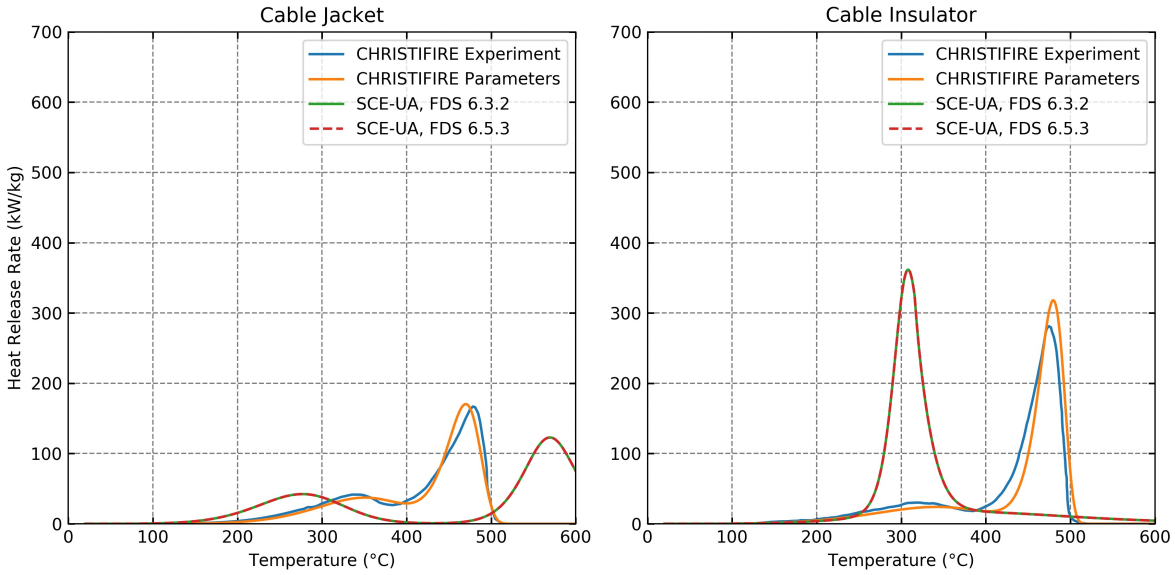


Figure 5: Micro-combustion calorimetry of cable components of cable #219. Comparison between experiment and simulation results of the reaction parameters provided by CHRISTIFIRE Phase 1 and results of the IMP (SCE-UA).

As mentioned above, each cable component was divided into two materials (MATL) to cover the two pyrolysis reactions, (reaction A and reaction B). Both MATL of a cable component yield surrogate fuel and a residue. The yields were taken from the MCC results of the CHRISTIFIRE report.
The IMP was provided with the heat release rate data (HRR) of one repetition of the 50 kW/m² Cone Calorimeter experiment as the target data.
The different parameter sets were then used within the MT-3 simulation setup to assess their performance in predicting the fire propagation in a cable tray installation.

RESULTS
In *Figure 5* the results of MCC tests from CHRISTIFIRE and simulations are shown. The results from the simulations with the parameters provided in the CHRISTIFIRE report match the experimental

results very well. The results out of the IMP show significantly different behaviour.
Cone Calorimeter data for irradiance levels of 25 kW/m² and 50 kW/m² are provided in *Figure 6*, for 75 kW/m² in *Figure 7*. Note that the SCE-UA worked with the Simple Cone simulation setup at 50 kW/m² external heat flux. For this case, experimental and simulation results match relatively well, as expected.

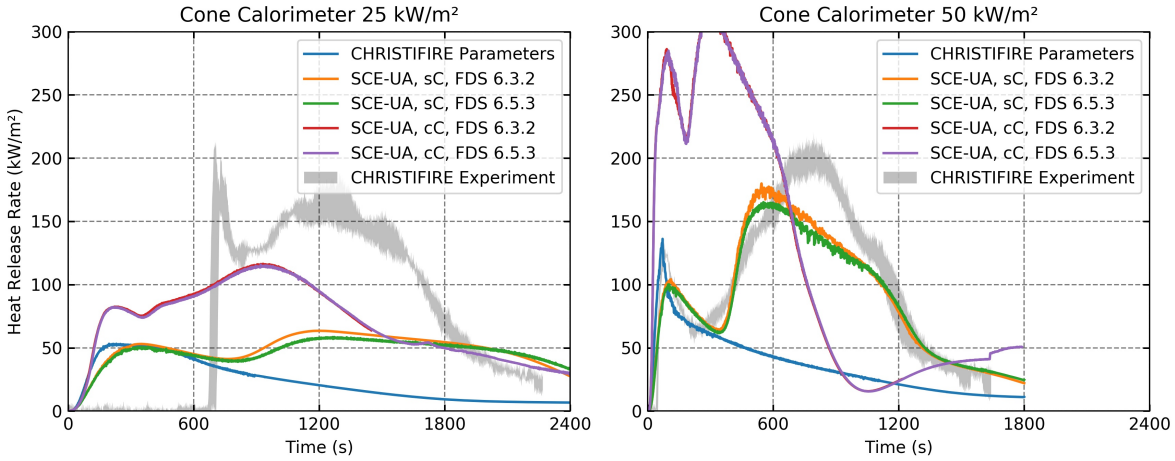


Figure 6: Cone Calorimeter test and simulation results for cable #219, at 25 kW/m² and 50 kW/m² incident flux. Comparison with reaction kinetics parameters provided by CHRISTIFIRE Phase 1 and the best parameter set of the inverse modelling process (SCE-UA). Simple Cone (sC) and Coarse Cone (cC) setups for different FDS versions.

The main features of the experimental results are visible in the simulation results, but slightly off. For 75 kW/m² the results are still similar to the experiment, however at 25 kW/m² the behaviour is significantly different. Increased cell resolution in the Coarse Cone setup improves the results for 25 kW/m² and 75 kW/m² but largely overestimates the results in the 50 kW/m² case. In general the direct transfer of the CHRISTIFIRE parameters is only able to cover the first peak at 50 kW/m² and 75 kW/m² but shows significantly different behaviour in all other cases.

During the CHRISTIFIRE experiments the HRR of the cable tray arrangements was estimated by the oxygen consumption method, as well as based on the mass loss rate. The results of the oxygen consumption method was chosen to compare them against the simulation results. For simulations of the tray setup it proved to be difficult to achieve fire propagation. In most of the simulations, the fire extinguished on its own, shortly after the burner was switched off. The parameter set based directly on the CHRISTIFIRE results showed only a small contribution to the total HRR of the fire, close to 10 kW.
The parameter set from the IMP showed a contribution of around three times the burner's input. After the burner was switched off, the HRR dropped by 40 kW recovered slightly (~10 kW) and then decayed slowly, similar as the FDS 6.5.3 results (*Figure 8*). Following the assumption that the material and reaction kinetics parameters are determined reasonably well during the IMP, focus was shifted to the heat transfer to the cable.
Three parameters were looked at, for the investigation of the influence on the radiative heat transfer: radiative fraction of the flame, soot yield and the surface temperature of the burner. After the investigation, the surrogate fuel was changed from methane to toluene, both are pre-tabulated in FDS. Thus, the radiative fraction of the flame changed from one of the lowest (0.2) to one of the highest (0.45) pre-tabulated values. Soot yield was set to 0.178 g/g based on textbook values for toluene [14]. The surface temperature of the burner was set to 410 °C with a slow decay rate, after the burner was turned off. Specifically the burner temperature was of greater importance as expected at first glance.

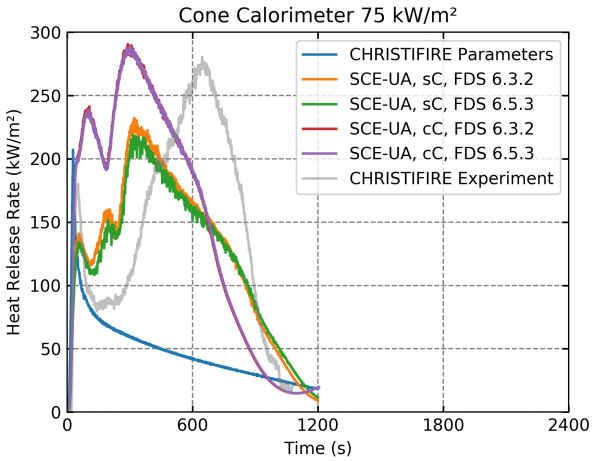


Figure 7: Cone Calorimeter test and simulation results for cable #219, at 75 kW/m² incident flux. Comparison with reaction kinetics parameters provided by CHRISTIFIRE Phase 1 and the best parameter set of the inverse modelling process (SCE-UA). Simple Cone (sC) and Cone (cC) setups for different FDS versions.

Thus, satisfactory fire propagation could be achieved in the simulated cable tray installation.It is important to note that the parameter set was adjusted after the IMP was finished, to achieve fire propagation.Furthermore, comparison of the two FDS versions, 6.3.2 and 6.5.3 shows nearly the same results for the MCC and Cone Calorimeter simulations. When comparing simulation results of the tray arrangement a significant difference is notable after the burner is switched off.

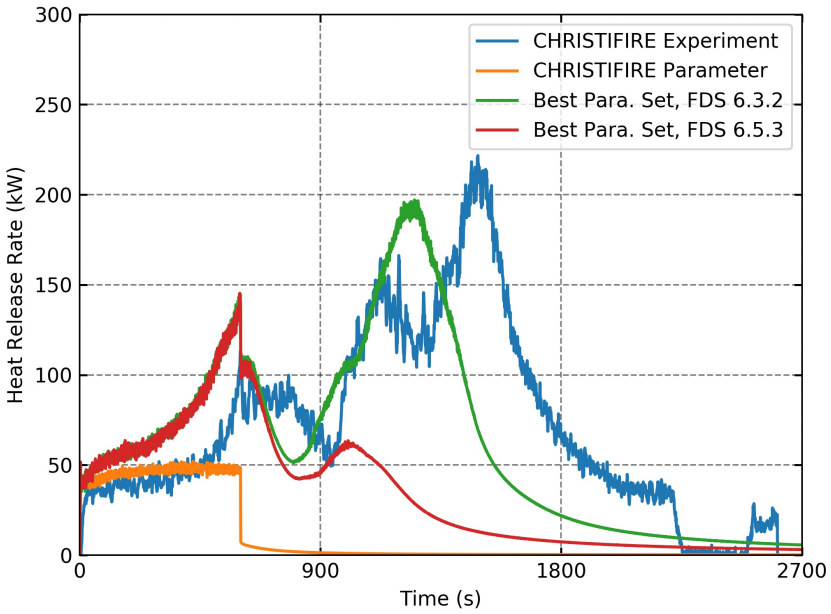


Figure 8: Comparison of Multiple Tray Test 3 from CHRISTIFIRE with simulation results of provided parameters, as well as the best parameter set from the IMP. The gas burner was switched off after 600 s. Highlighting also the influence of different FDS versions.

DISCUSSION

As a proof of concept, it was demonstrated that the simulation of fire propagation in cable tray arrangements is feasible within FDS. The set up IMP is able to generate parameter sets that are able to predict the general fire behaviour within a real-scale simulation setup, based on small scale experimental data. However, the parameter set performs relatively well only within a tight frame.

Furthermore, it is important to note that the user needs to be careful when attempting to transfer the material parameters between different versions of the simulation software. Specifically in the presented case, the parameters are model specific, also depending on the FDS version.
Additionally, the demonstrated process, to obtain a material parameter set for fire simulations, could possibly be used for all solid combustible materials. Cables are used as a specific example in this work.

The ability to predict the fire development, based on material parameters and environmental conditions near the fire, enables the user to create better assessments of possible fire and smoke spread, specifically in non-standard facilities. This is of interest, for example, within the (accelerator) tunnel and technical gallery infrastructure at CERN. Cables as a fire load, spread over long distances, from tens of meters up to kilometres. Narrow cross sections may lead to long stretches of cables being pre-heated which will promote the firespread, the extent of which is to be investigated in the future with the outcomes of this work. Obviously, this is not only limited to CERN, but of interest for all cases where cables are installed inside technical galleries, like data centres or power plants.
It is also of interest, how much material may be involved and turned into smoke during a fire incident. In the event of a fire in a particle accelerator tunnel, large parts of the accelerators would be condaminated with fire products, which are possibly activated. Soot, mainly carbon, could lead to short circuits. Substances like halogens form corrosive solutions with the humidity of the air and would lead to damage to the sensitive electronics of the accelerators and detectors. Cleaning the accelerators would most likely be performed manually and extremely expensive, also considering the possible long down time of the whole accelerator complex.
Furthermore, smoke production and movement is important to assess evacuation strategies in CERN's tunnel network. In some cases, egress routes can become quite long and useful compartementalisation strategies need to be defined.

Currently, the overall process is being revised and improved and some aspects of the envisioned improvements are presented in this paragraph.
One severe limitation has been the use of the result of only one experiment as target information. This has been changed to incorporate all repetitions of the Cone Calorimeter experiments with their respective incident heat fluxes as simulation setup for the upcoming optimisation runs.
In the beginning, the assumption has been that methane could serve as surrogate fuel, together with the given material parameters. However, after the IMP the surrogate fuel and the soot yield needed to be changed to achieve the desired fire propagation behaviour. For the upcoming runs of the IMP, the surrogate fuel and the soot yield will be set to the values of toluene right from the beginning.
The simplified simulation setup of the Cone Calorimeter contains some inaccuracies, like a very coarse mesh, the missing exhaust gas flow and a slightly large edge length. Those points will be addressed for future runs. Specifically smaller mesh cells, despite being costly in terms of computational resources, are desirable in order to better cover the interaction between sample surface and flame.
Furthermore, it can be seen in *Figure 5* that the chosen parameters, by the IMP, diverge significantly from the experimental data of the MCC. It is important to emphasis that the IMP was was working with material parameters, that were used in the simplified Cone Calorimeter environment with a model representing assembled cables. This means, in the MCC tests were performed on a tiny, homogenious material sample, under conditions that are aimed to specifically test the material behaviour and reduce influences from other sources. Those sources could be, for example, the geometry which could lead to an inhomogeneous heat up, thus an inhomogeneous pyrolysis. By using the configuration of a relatively large furnace with a tiny sample, the main factor for material pyrolysis can assumed to be the samples temperature, while others can be neglected. Due to limitations in FDS however, the representation of the circular cross section of cables is difficult. The chosen model, to represent the cables in the simplified Cone Calorimeter simulation, is inaccurate by using flat layers of material that are stacked upon each other. Therefore, the bumpy structure of the cables, that could be observed when multiple cables lie next to each other, is lost. This should affect the heating up of the cable model in comparison to the real experiment. Furthermore, in the real experiment, the degrading cable material may undergo chemical reactions that are not known here and

are not modelled. Thus, it might be necessary to use artificial parameters for reaction kinetics to account for model inaccuracies, and is also expected to some degree. Still, it needs to be investigated if the optimisation algorithm shall have free reign over the reaction kinetics parameters or if it requires some constraints.

With the revised process, more of the CHRISTIFIRE cables will be treated. Followed by non-halogenated cables, which have been tested, within the framework of the FCC Fire Safety Collaboration, at Lund University, Sweden.
In addition, the implications of the changes in the radiation and solid heat transfer models between the FDS versions 6.3.2 and 6.5.3 need to be further assessed. Furthermore, the Python scripts are also in an improvement process to set them up in a more general way. This will allow faster changes in the setups to be investigated. A small group of people came together at the University of Wuppertal, Germany, and started the creation of a flexible Python framework to tackle similar inverse modelling problems (working title: propti).

Note: Part of the data used for creating this paper, is publically available on the Zenodo data base under the following DOI: 10.5281/zenodo.1145947

ACKNOWLEDGEMENTS
The authors want to thank Kevin McGrattan for providing advice, access to the CHRISTIFIRE data and fruitful discussions.

Furthermore, the authors would like to thank their collegues of HSE at CERN for their valuable input and proof reading.

Part of this work is sponsored by the Wolfgang Gentner Programme of the Federal Ministry of Education and Research of Germany.

Within the study project of the Future Circular Collider, a fire safety engineering collaboration with other particle laboratories was established. Members of this group are some of the major particle accelerator facilities (CERN, DESY, ESS, FNAL and MAX IV) and Lund University. It is aimed towards a better understanding of smoke production and movement in one-of-a-kind underground research facilities, e.g. such as particle accelerators, benefitting life, environment and asset protection. The authors are thankful for all the discussions and advice coming out of this collaboration.

The authors gratefully acknowledge the computing time granted by the JARA-HPC Vergabegremium and VSR commission on the supercomputer JURECA at Forschungszentrum Jülich, Germany.

REFERENCES

[1] “CERN in Numbers,” [Online]. Available: https://smb-dep.web.cern.ch/en/content/cern-numbers. [Accessed 12 October 2017].

[2] C. Lefèvre, “CERN Document Server,” December 2008. [Online]. Available: https://cds.cern.ch/record/1260465?ln=de. [Accessed 11 10 2017].

[3] K. McGrattan, A. Lock, N. Marsh, M. Nyden, S. Bareham and M. Price, “Cable Heat Release, Ignition and Spread in Tray Installations during Fire (CHRISTIFIRE), Phase 1: Horizontal Trays,” Office of Nuclear Regulatory Research, 2012.

[4] A. Meunders, L. Arnold and B. Schröder, “Automated Generation and Evaluation of FDS Simulations for Optimizing Parameters with Dakota,” in *Magdeburger Brand- und Explosionsschutztag*, Magdeburg, 2015.

[5] A. Meunders, G. Baker, L. Arnold, B. Schröder, M. Spearpoint and D. Pau, “Parameter optimization and sensitivity analysis for fire spread modelling with FDS.,” in *10th International Conference on Performance-Based Codes and Fire Safety Design*, Brisbane, Australia, 2014.

[6] A. Matala, “Methods and applications of pyrolysis modelling for polymeric materials,” Technical Research Centre of Finland, Espoo, 2013.

[7] C. W. Lautenberger, “A generalized Pyrolysis Model for Combustible Solids,” University of California, Berkeley, 2007.

[8] M. Andreini, L. Arnold, T. Hehnen and S. L. Mendola, “A Probabilistic Model for the Prediction of the Energy Release Rate from the Combustion of Electrical Cables,” in *IFireSS - 2nd International Fire Safety Symposium*, Naples, Italy, 2017.

[9] K. McGrattan, R. McDermott, C. Weinschenk, S. Hostikka, J. Floyd and K. Overholt, “Fire Dynamics Simulator User's Guide,” U.S. Departement of Commerce, USA, Maryland, Gaithersburg, 2015.

[10] R. E. Lyon and R. N. Walters, “Pyrolysis Combustion Flow Calorimetry,” *Journal of Analytical and Applied Pyrolysis,* vol. 71, no. 1, pp. 27-46, 2004.

[11] B. T. Rhodes, “Burning Rate and Flame Heat Flux for PMMA in the Cone Calorimeter,” 1994.

[12] Q. Y. DUAN, V. K. GUPTA and S. SOROOSHIAN, “Shuffled Complex Evolution Approach for Effective and Efficient Global Minimization,” *Journal of Optimization Theory and Applications,* vol. 76, no. 3, pp. 501 - 521, 1993.

[13] T. Houska, P. Kraft, A. Chamorro-Chavey and L. Breuer, “SPOTting Model Parameters Using a Ready-Made Python Package,” *PLOS ONE,* 17 December 2015.

[14] M. J. Hurley, Ed., SFPE Handbook of Fire Protection Engineering, 5th ed., New York Heidelberg Dordrecht London: Springer, 2016.