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Taking a detailed cross section out of a 3D model to increase performance and accuracy

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Abstract
This paper presents an approach to increase performance by splitting a 3D model into two model parts. The approach is general, but best presented by an example. The use case is the hot spot temperature in a three-core power cable. The detailed cable cross section with metallic screens and armouring is removed from the 3D model and simulated in a separate 2D model. Two applications are presented. The first case is crossing of cable ducts in ground by a right angle at different depths. The second example is a power cable in a J-tube. The geometry of the J-tube is so simple that it can be modeled in 2D as well, which in turn allows for direct coupling of the two 2D model components. This paper presents the modeling approach and compares the first example with a full 3D model with respect to performance and multiphysics capability.
Keywords: 3D, cross-section, performance, segregation.

Introduction
When going from 2D to 3D modeling the resolution of the mesh goes down and the demand for memory increases considerably. As a consequence, it is more difficult to simulate multiphysics or challenging physics like convection of air with high accuracy. A common compromise is neglecting some of the physics in 3D. Travis, *et al*. [1] present an example where spitting a 3D model into two model parts increases performance. Here, another approach is presented. If the 3D model contains a long part with constant cross section, like a cable, it can be moved to a 2D cross-sectional model component and coupled to the remaining 3D model. This greatly reduces the number of mesh elements without losing geometric details. It is enough with one cross-sectional model for all cables in the 3D model.
This paper presents examples with a three-core power cable. A similar solution for a twisted cable splits the cable itself into a 3D model of the metal parts for electromagnetic losses and a detailed 2D cross section for heat transfer, radiation and convection [2]. This is for one straight twisted cable, whereas the approach presented here works for cables routed in any way in 3D. For instance COMSOL®s loft function in the Design module could be used to generate more complex cable routing in 3D. The more complex the geometry, the larger the 3D model and the higher the benefit of the presented approach.
In the first example, two pairs of power cable ducts cross three other pairs by a right angle at different depth in ground. The hot spot temperature is of interest. The second example is a J-tube with a power cable, which is common in offshore platforms. It presents one straight cable in 3D. As the geometry is so simple, it is possible to use a 2D geometry for the environment, and to directly couple the temperature and heat flux between the cable and the J-tube by probes. This results in an easy and elegant small model with minimum computational requirement.

Theory
Example 1: Crossing of buried cable ducts
Consider a three-core cable in a duct in soil with heat losses in the conductors. Due to continuity the heat flux out of the duct into surrounding soil is the same. Since the heat is generated in the conductors, there is a temperature gradient from the conductors to the duct outer surface. Neglecting the temperature coefficient of the conductor resistivity, the temperature offset ΔT of the conductors compared to the duct outer surface is constant. The temperature along the ducts can vary, but the cross-section is unchanged. The temperature offset can be measured by a 2D cross-sectional model with surrounding soil. Knowing the offset, the cable ducts can be removed from the 3D model and be replaced by a surface heat flux into soil corresponding to heat losses in the conductors. This modified 3D model will also simulate the surface temperatures along the ducts. For a certain location, the cable conductor temperature is obtained by adding the temperature offset. The highest duct surface temperature will translate to a hot spot in the cable conductor. The temperature pattern of the full cross-section is obtained by the 2D model of the cable in duct by setting the right ambient temperature.
Including the temperature coefficient of the copper conductor α_{Cu} the heat flux q will be higher for conductor temperatures above 20 °C:

$$q = q_0\left(1 + \alpha_{Cu}(T_{duct} + \Delta T - 20°\text{C})\right) \qquad (1)$$

A parameter sweep varies the ambient temperature and the difference between the conductor temperature and the temperature on the duct outer surface is plotted. This gives a line with slightly increasing slope. For simplicity the average value is used here. Alternatively, one could use the offset occurring close to the hot spot temperature in order to maximize accuracy there.

Example 2: Vertical J-tube

Splitting the model into two different parts can have a number of further advantages. The J-tube is a special case with only one straight tube. Thus, the J-tube model part can be modelled in 2D axial-symmetry. A single-core cable would be axial-symmetric, but a three-core cable is not. Another advantage is that the J-tube geometry can be oriented vertically. This gives the right orientation for the natural convection of air inside the tube. If natural convection was simulated in the 2D cross-section of the cable, the cable would be horizontal, which is wrong. Another advantage is that the J-tube geometry is simple enough that a lazy approach can be tolerated. The temperature and the heat flux on the cable outer surface can be coupled directly between the two models by probes. This skips the parameter sweep, but the cross-sectional model uses average values of temperature and heat flux from the other model part. This is elegant, but it has a similar effect as neglecting the temperature coefficient of the conductor. Also, simulating two 2D components together in the same model is not expensive.

The model

Cross-section and materials of cable ducts

Figure 10 in the Appendix shows the simulated cable in the duct. The dimensions are given in Table 2 and the thermal properties and external conditions in Table 3 and Table 4.

The upper surface of the soil is set to a constant ambient temperature for air or water. The other sides of the soil are modeled as thermal insulation. In the cables and in soil, heat conduction is simulated. The space in the duct around the cable is filled by betonite. The temperature coefficient of the cable copper conductor is included.

3D arrangement of the cable ducts in soil

The cable ducts buried in ground can be seen in Figure 8. It shows five ducts. The model uses horizontal symmetry. The two upper ducts effectively extend to two duct pairs and the three lower ducts extend to three duct pairs. The effective volume is four times larger than the simulated. The horizontal distance between adjacent duct pairs is constant. The dimensions are in Table 5.

3D model and segregated model

The cable ducts in soil is first simulated by a single 3D model with a cable in each duct. For the segregated model the ducts and cables are removed from the soil leaving straight holes in the soil. On the ducts outer surfaces the radial heat flux is set by a boundary condition as a function of the temperature. The relation is obtained by the 2D model in Figure 1 of the cable duct surrounded by soil. The four outer parts in the figure are modeled as COMSOL®s infinite geometry. The ambient temperature on the outer boundaries in the figure is varied by a parameter sweep in order to measure the temperature offset to the conductors for each average temperature on the duct outer surface. The heat loss q_0 in the conductors for 20 °C is set to 15 W/m. In the model the surface temperature on each point of the duct is given by a COMSOL® internal variable of the heat transfer module, *ht.Tvar*, which becomes visible when Equation View is enabled. It is used by extending the surface boundary condition to Eqn. (1). COMSOL®s Learning Center explains thoroughly how to couple physics between model components [3].

The parameter sweep is also performed with multiphysics simulations and air-filled ducts without a 3D model to compare with.

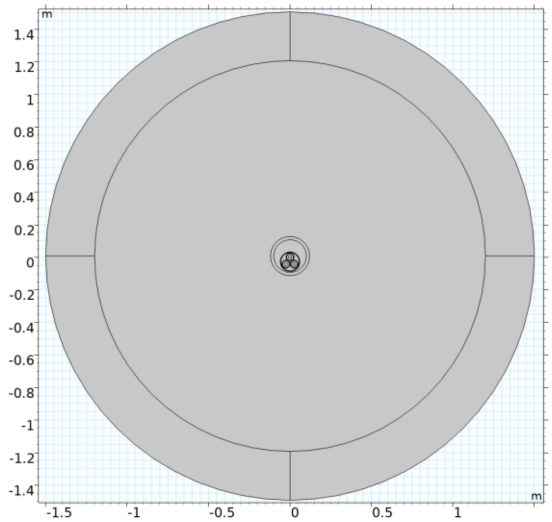

Figure 1. 2D geometry of cable duct in infinite soil used for temperature sweep.

Simulation Results

Crossing of buried cable ducts with 3D model

From the predefined mesh sizes “normal” worked when reducing the minimum element size from 0.27 m to 0.02 m, where the resulting conductors still looked like squares. “Extremely fine” was used to yield agreement between the applied heat source and heat measured by integration. Inside the ducts a meshing scale factor of 0.2 in duct direction reduced the number of mesh elements to a fraction without changing the results. For convergence it was necessary to reduce the physics to heat conduction and the air in the cable ducts was filled with a solid, bentonite. Radiation could be simulated, but solid air or transparent bentonite are no realistic materials. Figure 8 in the Appendix shows the simulated duct surface temperature. The hottest location with 50.4 °C is at (1 m, -2 m, 6 m). Figure 10 shows the cable temperature at this point.

Crossing of buried cable ducts with segregated model

The simulations above were reproduced with the segregated model. First, the 2D cross-sectional model gave the temperature offset ΔT from the duct outer surface to the conductors. Without temperature coefficient of the conductor it is 6.75 K. With temperature dependency α the relation becomes the line in Figure 2. The duct temperature varies between 34°C and 51°C, where the temperature offset varies a little bit around 7.5 K. The average heat flux increased from 15 W/m to 16.8 W/m per cable.

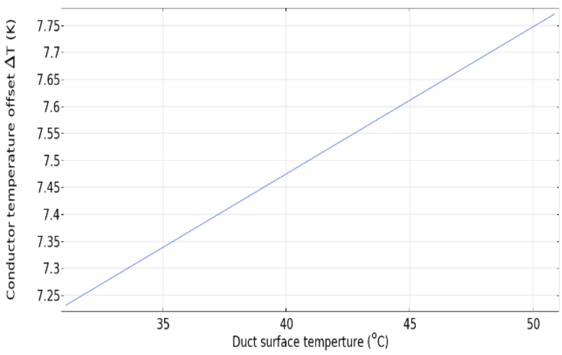

Figure 2. Temperature offset from duct outer surface to cable conductors with heat conduction.

Figure 9 and Figure 11 show the results for the segregated model. Table 1 summarizes the results. The cable hot spot temperatures differ by 2 K from the conventional 3D model. Neglecting the temperature coefficient of copper the maximum temperatures were 5 K lower in both models and the difference between the models was around 1 K. A reason for the lower hot spot temperature of the 3D model is a 3D effect. Good electrical conductors are good thermal conductors. Copper and steel leak heat in axial direction. For verification, a low thermal conductivity of 3 W/(m·K) in the metals is high enough to keep the radial temperature gradient unchanged. The hot spot on the ducts and in the conductors increased to 50.9 °C and 59 °C, respectively.

***Table 1**: Comparison of results*

Item	3D model	Segregated
Mesh size	Extremely fine	Finer
DOFs	114 Millions	1.6 Millions
Physical memory	303 GB	8 GB
Solution time	45 min 11s	2 min 15 s
Hot spot duct	50.4 °C	51.7 °C
Hot spot cable	57.3 °C	59.5 °C

Crossing of buried cable ducts with segregated multiphysics model

The conventional 3D model was limited to heat conduction, whereas the segregated model works with full multiphysics. The electric current was set in the conductors instead of guessed resulting heat losses. The following case includes an AC current of 275 A with phase shifts of 120° as source of conductor losses of about 15 W/m. Bentonite was replaced by air with natural convection. The resulting losses in the metallic screens became 4.5 W/m and in the armouring 0.5 W/m such that the total losses sum up to 20 W/m. Cross-bonded or solidly grounded screens have induced currents with losses. The new temperature offset in Figure 3 does not increase like in Figure 2.

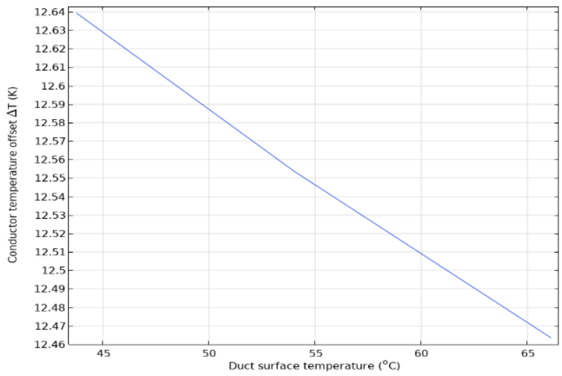

Figure 3. Temperature offset from duct outer surface to cable conductors with multiphysics calculations.

With the new losses of 20 W/m and a temperature offset of 12.6 K the warmest location on the ducts has 67.1 °C. There, the hot spot in the cable is 79.6 °C, see Figure 4.

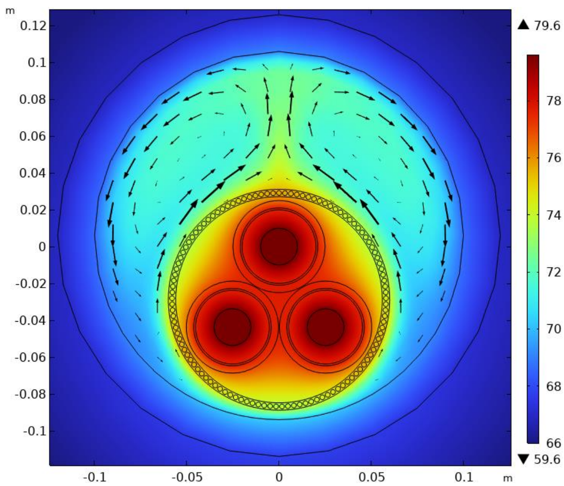

Figure 4. Hot spot temperature by segregated multiphysics model.

Power cable in J-tube with segregated multiphysics model

As before, the model part with the cable cross-section can simulate advanced electromagnetic heating. Figure 5 shows the currents. The difference is that the cable surface temperature of 61.3°C in Figure 6 is the average obtained by a probe in the J-tube part. The hottest cable surface temperature is 75.8°C at the top of the J-tube in Figure 7. Adding

14.5 K to the conductor temperature gives 81°C. The temperature coefficient of copper is simulated here for 66.5 °C instead of 81 °C. The resistance, heat loss and temperature rise should be 6% higher. 84 °C is still below the limit of 90°C for XLPE.
The J-tube geometry is only a vertical rectangle, which allows for advanced thermal physics including natural convection of air, see Figure 7. It includes radiation from the cable surface to the J-tube inner surface, radiation of the J-tube outer surface to the environment and a heat transfer coefficient on the vertical J-tube towards the environment. One observation is that even in 2D convection is demanding if the geometry is too large.

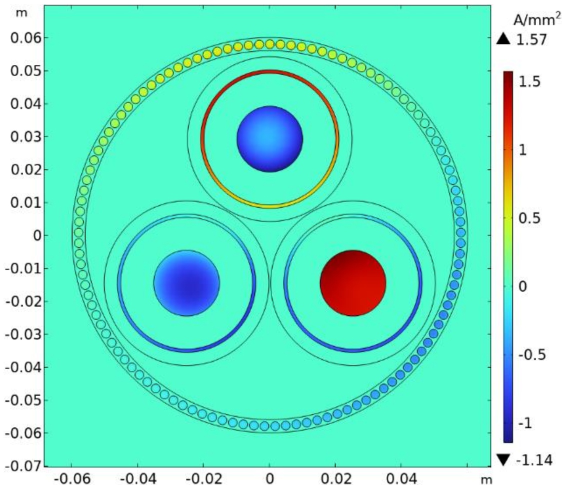

Figure 5. Detailed three-core cable cross-section showing imposed AC current with 120 degrees phase shift and resulting eddy currents.

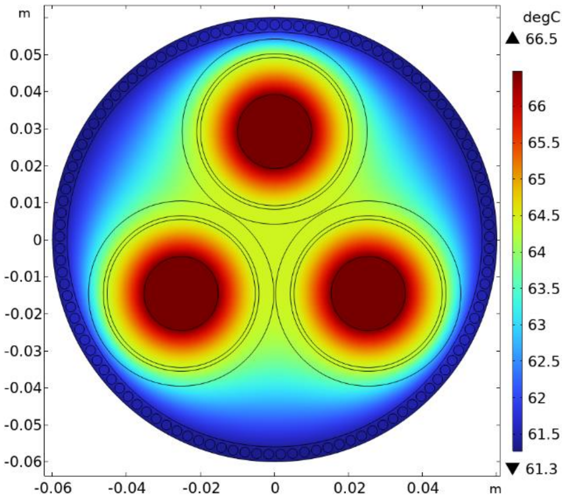

Figure 6. Cable temperature for average cable surface temperature.

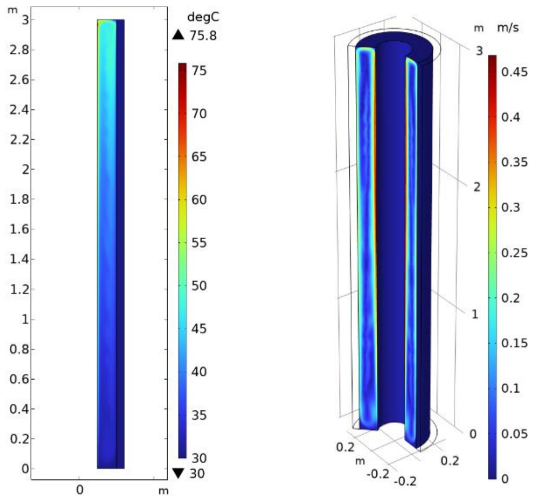

Figure 7. Results of J-tube model part. Left: Temperature. Right: Revolution plot of natural convection of air.

Conclusion

A constant cross-section can be moved out of a 3D model with similar results. By design the method cannot account for 3D effects perpendicular to the cross section. This is conservative in the application with the cable.
The simulations also show that 3D models have lower mesh resolution than 2D models and may need simplified physics for convergence. The segregated model works in full multiphysics, which makes it easier to create a realistic model.
The computational cost in terms of memory requirement and solution time is reduced to a fraction.
It was further illustrated that the approach can be simplified in special cases of a split model.
A constant temperature offset from the duct surface to the conductors works well. In a case with different metals as source of losses it could be easier to measure the dependency of the heat flux on the duct temperature directly and apply curve fitting.

References

[1] e. a. A. R. Travis, "Simulating HFIR Core Thermal Hydraulics Using 3D-2D Model Coupling," in *Comsol Conference*, Boston, 2013.

[2] J. C. d.-P.-L. P. Cruz-Romero, "Hybrid 2D/3D fully coupled electrothermal model for three core submarine armored cables," in *Comsol Conference*, Munich, 2020.

[3] COMSOL, [Online]. Available: https://www.comsol.com/support/learning-center/article/36911.

Appendix

***Table 2**: Dimensions of 3-core cable and duct*

Part	**Radius**
Conductor	10 mm
Conductor insulation	20 mm
Copper screen	21 mm
Cable core	25 mm
Cable filler	56 mm
Cable	60 mm
Duct inner	100 mm
Duct outer	120 mm

***Table 3**: Materials thermal properties*

Material	**Thermal conduc-tivity *k* [W/mK]**	**Density ρ [kg/m³]**	**Heat capacity *Cp* [J/(kgK)]**
Copper	400	8960	385
Steel	44.5	7850	475
Insulation (sheath, filler, duct)	0.3	1000	2000
Betonite	1	1000	2000
Soil	1	2000	1000

***Table 4**: Other thermal parameters*

Property	**Value**
Emissivity of cable surface and duct inner surface for air-filled duct	0.9
Ambient water temperature	15 °C
Temperature coefficient of copper α_{Cu}	0.00393/K
Heat loss q_0 in each of the three conductors	5 W/m

***Table 5**: Position of ducts in soil*

Radius	**Size**
Length and width of soil	15 m
Height of soil	10 m
Height of upper ducts	7 m
Height of lower ducts	6 m
Distance between two duct pairs, duct center to duct center	4 m
Distance between two ducts of same pair duct center to duct center	3 m

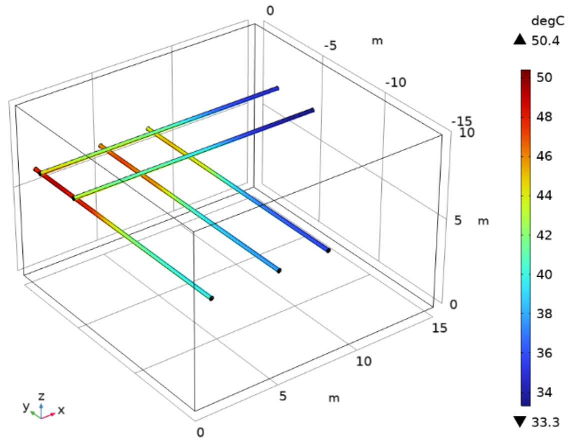

Figure 8. Ducts surface temperature by 3D model with heat conduction.

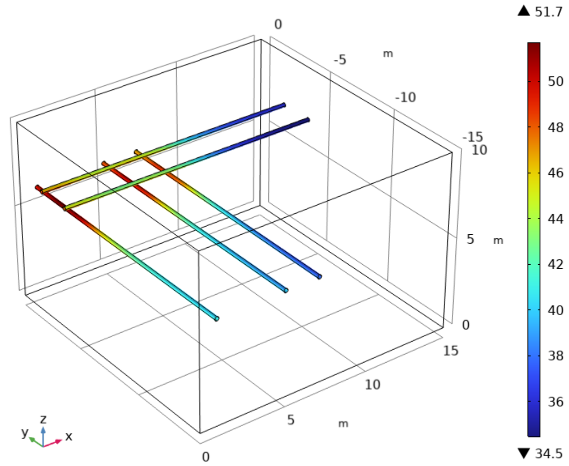

Figure 9. Ducts surface temperature by segregated model with heat conduction.

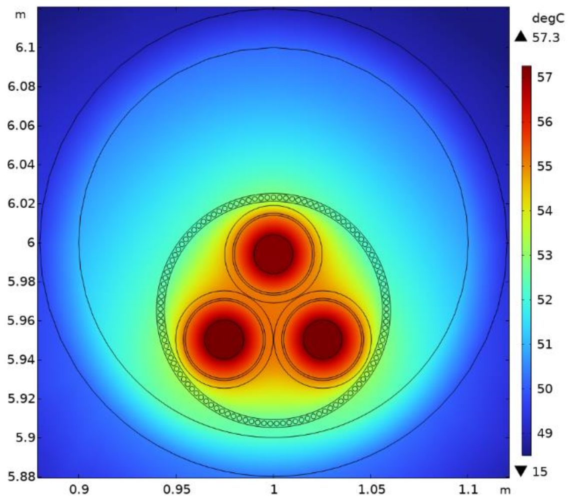

Figure 10. Hot spot temperature by 3D model with heat conduction.

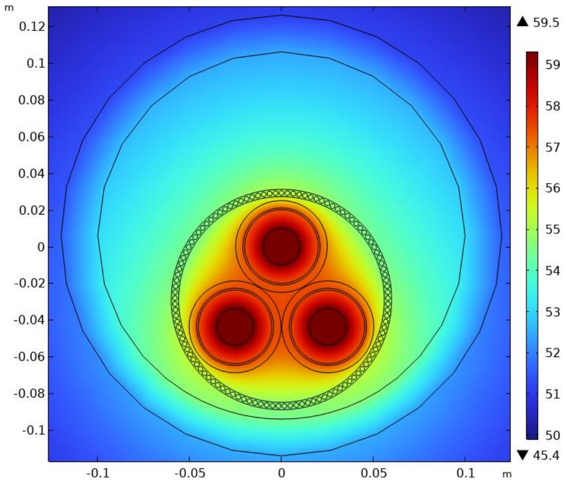

Figure 11. Hot spot temperature by segregated model with heat conduction.